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DEVELOPMENT OF A METHOD FOR ESTABLISHING RESURFACING PRIORITIES FOR THE PAVEMENT MANAGEMENT SYSTEM IN INDIANA: VOL. II - STUDY PROCEDURES AND RESULTS

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Final Report

DEVELOPMENT OF A METHOD FOR ESTABLISHING RESURFACING PRIORITIES FOR THE PAVEMENT MANAGEMENT SYSTEM IN INDIANA

TO:	H.L. Michael, Director Joint Highway Research Project	July 3, 1984 Revised May, 1985
FROM:	K.C. Sinha, Research Engineer Joint Highway Research Project	Project: C-36-63I File: 9-7-9

Attached is the Final Report on the HPR Part II Study entitled, "Development of a Method for Establishing Maintenance Priorities for the Pavement Management System in Indiana." The research was conducted by Mr. Benjamin Colucci-Rios under the direction of Professors K.C. Sinha and E.J. Yoder.

The report here documents the data used, the procedures followed, the models developed, and model results. Recommendations for incorporating the study findings in the IDOH Pavement Management System are also included. It should be noted that the study findings have already been presented to the members of the IDOH Pavement Management Task Force by Mr. Colucci and Professor Sinha in a workshop held on May 7, 1984.

The report contains three volumes; Vol I provides an executive summary, Vol II presents the study procedures and results, and Vol III includes the appendices.

This report is forwarded for review, comment and acceptance by the IDOH and FHWA as fulfillment of the objectives of the research.

Respectfully submitted,

K.C. Sinha
Research Engineer

KCS/jaj

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16. Abstract

This report describes a methodology for establishing resurfacing priorities at the network level that can be incorporated in the pavement management system of the Indiana Department of Highways. As a part of this methodology two optimization models were developed. As a companion tool a technique based on graphical approach was also proposed. The methodology was applied to the Indiana interstate highway network using 1982 as the base year. The results showed that Indiana's normal level of budget during the next five years can optimally resurface about 85 percent of the total center-line miles classified as deficient during this period. A sensitivity analysis on budget was also conducted.

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TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

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LIST OF SYMBOLS AND ABBREVIATIONS

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
ASTM	American Society for Testing and Materials
CALTRANS	California Department of Transportation
CDV	Corrected Deduct Value
CE	Cost Effectiveness Index
CEPI	Equivalent Performance Index Complement
CERL	Construction Engineering Research Laboratory
CI	Condition Index
CLM	Center-line miles
COPES	Concrete Pavement Evaluation System
CRC/CRCP	Continuously Reinforced Concrete Pavement
CS	Deficient Contract Sections
CSW	Contract Section Worth
D	Sum of individual deducts
DI	Distress Index
DM	Distress Manifestations
DMS	Danish Management System
DOT	Department of Transportation
EAL	18-Kip Equivalent Axle Load
ECN	Engineering Computer Network
EPI	Equivalent Performance Index
ER	Engineering Rating
FHWA	Federal Highway Administration
FI	Final Index
FN	Friction Number
HAE	Hot Asphalt Emulsion
HAC	Hot Asphalt Concrete
IBM	Industrial Business Machines
IDOH	Indiana Department of Highways
IDT	Idaho Department of Transportation
IP	Integer Programming
JHRP	Joint Highway Research Project
JPCP	Jointed Plain Concrete Pavements
JRC/JRCP	Jointed Reinforced Concrete Pavements
L	Length of pavement section
LINDO	Linear Interactive and Discrete Optimizer
LP	Linear Programming
MIPZIM	Mixed-Integer Programming Zero-One
MMS	Maintenance Management System

LIST OF SYMBOLS AND ABBREVIATIONS (Continued)

MPOS	Multi-Purpose Optimization System
MPS	Mathematical Programming System
MRN	Mean Roughness Number
NDT	Non-Destructive Testing
NOS	Network Optimization System
NREHAB	Number of Feasible Rehabilitation Activities
NVAR	Number of Variables
OAW	Overall Aggregated Weight
ODOT	Ohio Department of Transportation
OR	Operational Rating
P	Priority Index
PCA	Portland Cement Association
PCC	Portland Cement Concrete
PCI	Pavement Condition Index
PI	Priority Index
PINS	Pavement Information and Needs System
PMMS	Pavement Maintenance Management System
PMS	Pavement Management System
PPMIS	Pavement Performance Management Information System
PQI	Pavement Quality Index
PRI	Present Rideability Index
PSI	Present Serviceability Index
PSR	Present Serviceability Rating
PWOC	Present Worth of Cost
R	Road Contracts
R&TC	Research and Training Center
RCI	Riding Comfort Index
RCR	Riding Comfort Rating
RMC	Routine Maintenance Cost, $/center-line mile/year
RN	Roughness Number
RS	Resurfacing contracts
SAI	Structural Adequacy Index
SDDOT	South Dakota Department of Transportation
SI	Structural Index
SN	Skid Number
SPSS	Statistical Package for Social Sciences
SR	Structural Rating
T	Overlay Thickness, inches
%T	Percent Trucks
TAD	Total Accumulated Directional ADT
TDV	Total Deduct Value
TPRC	Total Project Resurfacing Cost
TRC	Total Pavement Resurfacing Cost, $/center-line mile
TSI	Terminal Serviceability Index
VCI	Visual Condition Index
WSDOT	Washington State Department of Transportation
g	Annual Traffic Growth Rate
lbs.	Pounds
n/s	Not Selected
sys	Square Yards

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TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

CHAPTER 1

INTRODUCTION

General Background

One of the greatest engineering accomplishments in modern times, which is largely responsible for the nation's unprecedented growth and standard of living, is the 2 million miles of paved roads. The paved road system is the most important feature of the highway transportation system. Although the paved road system comprises only 51 percent of this nation's 3.9 million miles of roads, it carries 99 percent of all cattle, 85 percent of all fruits and vegetables, and 91 percent of all textile and leather products to retailers and wholesalers [1]. It is also important to note that other modes of transportation, such as air, rail, and pipeline, depend on the highway system in order to transport bulk goods from airports, stockyard and terminals to market and consumer. Even a large percentage of military equipment and personnel moves by road, and national defense plans recognize the importance of the highway system for effective response for any military emergency.

The heavy traffic in the United States is primarily carried by the interstate, arterial, and collector roads

within the paved road system. Even though they comprise only 31 percent of the total highway mileage in the United States, they carry 87 percent of the traffic.

The pavement structure is by far the largest single element of cost within the highway system. It represents between 30 and 50 percent of the total highway capital expenditures [2]. In 1981, for example, the overall cost of the interstate system was estimated at about $3 million per mile [3]. Since the establishment of the Highway Trust Fund in 1956, about $74 billion has been invested in the interstate system by federal and state governments and over $100 billion dollars on all classes of pavements [2].

After 25 years of providing adequate service, the highway pavements are now beginning to fall apart. By 1975 more than 100,000 miles of interstate, arterial, and collector roads were already rated as "fair" and 4,000 miles were in "good" but degenerating into "fair" condition [1]. In 1976 it was estimated that 4 percent of the interstate pavements needed immediate major rehabilitation [4]. In 1978, this figure already increased to 10 percent of the total interstate network [4]. By 1980 it was reported that pavements were deteriorating twice as fast as they could be rehabilitated [1]. In 1981, the Federal Highway Administration (FHWA) conducted a nationwide study and estimated that about $17 billion would be required during the next 10 years for

resurfacing, restoration, and rehabilitation of only interstate pavements to keep the system at an acceptable level of service [3]. It was estimated that if nothing was done by 1985, pavements would be deteriorating about three times faster [1].

The importance of rehabilitating existing pavements was first recognized in the 1978 Surface Transportation Assistance Act [3]. This act authorized $175 million for fiscal year 1981 and $275 million for fiscal years 1982 and 1983 for rehabilitation, resurfacing, and restoration of the interstate system. Subsequently, the 1983 Interstate 4-R funding level was increased to $800 million. For years 1984 through 1987, the Administration bill would provide levels of 1.3, 2.0, 2.1, and 2.7 billion, respectively. Unfortunately, these funds are still not sufficient to maintain the highway system at desirable standards. The need for maintaining and preserving the existing highway system, primarily the pavement structure, is a concern of all highway agencies.

The Need for Pavement Management

In recent years state and federal highway agencies have been working extensively in trying to develop a systematic, efficient, flexible, and cost-effective procedure for

scheduling maintenance and rehabilitation activities on existing pavements rather than constructing new ones. Indiana, for example, has constructed only 384 miles during the last 20 years and the 1984 and 1985 estimates for new construction are only 10.1 and 8.8 miles, respectively. Many state highway agencies have already developed and implemented these procedures which became known as Pavement Management Systems, or simply PMS. At the present time Arizona, California, Florida, Idaho, Kentucky, New York, Ohio, Utah, Washington and Texas have developed systematic procedures for scheduling maintenance and rehabilitation activities at both the network and project levels [5,6,7,8,9,10,11,12,13, 52].

One of the most important aspects which should be considered in the development of any pavement management system is that the procedure should be able to evaluate alternative maintenance and rehabilitation strategies for all types of pavements, not only on a yearly basis, but in a multi-year framework. It should also be able to accomplish the following goals:

1. It should be simple so it can provide the necessary information to the decision-makers in the most direct and productive manner.

2. It should be flexible so it can be modified and updated within a relatively short period of time.

3. It should be management oriented so it can provide information on optimal number of miles to be resurfaced under a given set of resource constraints such as budget, materials, equipment, manpower, and so on.

Background of the Research Study

The Indiana Department of Highways (IDOH) through the Research and Training Center (R&TC) has been collecting pavement roughness measurements on a continuing basis for the entire highway system since 1979 and pavement friction measurements since 1970. These data are summarized annually along with other information which includes average daily traffic (ADT) in one direction, surface type and texture, contract number, length, and last time a major rehabilitation was performed. This information is distributed to District and Central Office personnel and currently forms the basis for most of the decisions related to major rehabilitation primarily in the interstate system. Surface roughness number of a section is an indicator of highway user perception about the rideability of the section. Low skid resistance measurements are good indicators of how slippery a particular pavement section is. Although this information is

very useful in identifying pavement sections exceeding the minimum acceptable values established by the state on any given year, they are not useful in the process of selecting those miles that have the greatest need given a constraint in terms of the amount of money available for major rehabilitation. For an effective management approach, it is necessary to have a mathematical model that can answer questions such as:

1. Which specific pavement contract sections as well as how many miles of road should be rehabilitated during a given year or during the time frame specified with the available budget?

2. What type of maintenance strategy should be applied to the pavement contract sections selected in order to use the total available budget in the most cost-effective manner?

3. How many additional lane-miles can be improved if the budget is increased by a certain percentage?

4. How much additional budget is required to upgrade the pavement condition of the entire network or a part of it to a minimum acceptable level?

Status of Indiana Highways

The state of Indiana has an extensive pavement network which consists of approximately 91,700 miles of roads and streets of which about 30,000 corresponds to the Federal-aid primary and secondary system [14]. Tables 1.1 and 1.2 show the mileage distribution according to present serviceability rating (PSR) and functional classification during 1981 for rural and urban roads, respectively [14]. It can be noted that although a very few miles are classified as being "deteriorated" (6.8 percent and 1.2 percent for rural and urban roads, respectively), nevertheless there is a very high percent of roads within the "fair" category (56.4 percent and 44.9 percent for rural and urban roads, respectively). This means that unless something is done soon a large number of pavement sections is likely to fall in the "deteriorated" category in the near future. These percentages correspond to 12,979 miles in the rural system and 2,531 miles in the urban system. In so far as the interstate rural system in Indiana is concerned, only 20.9 percent is classified in "fair" condition, but is rapidly degenerating into "poor" or "deteriorated" condition. On the other hand, the interstate urban system has only 3 percent classified in "fair" condition and degenerating into "poor" condition.

Table 1.1 Distribution of Rural Mileage by Present Serviceability Rating and Functional Classification During 1981. [14]

Functional Classification	Present Serviceability Rating (PSR) Deteriorated 0.1-2.4	Fair 2.5-3.4	Good 3.5-5.0	Total
Interstate	-	179	676	885
	-	(20.9)	(79.1)	(100.0)
Other Principal	3	285	831	1119
Arterial	(0.3)	(25.4)	(74.3)	(100.0)
Minor Arterial	-	730	2363	3093
	-	(23.6)	(76.4)	(100.0)
Major Collector	240	5724	2984	8948
	(2.7)	(64.0)	(33.3)	(100.0)
Minor Collector	1315	6061	1597	8973
	(14.7)	(67.5)	(17.8)	(100.0)
Total	1558	12979	8451	22988
	(6.8)	(56.4)	(36.8)	(100.0)

Table 1.2 Distribution of Urban Mileage by Present Serviceability Rating and Functional Classification During 1981. [14]

Functional Classification	Present Serviceability Rating (PSR) Deteriorated 0.1-2.4	Fair 2.5-3.4	Good 3.5-5.0	Total
Interstate	-	8	251	259
	-	(3.1)	(96.9)	(100.0)
Other Freeways and	-	23	107	130
Expressways	-	(17.7)	(82.3)	(100.0)
Other Principal	3	560	755	1318
Arterial	(0.2)	(42.5)	(57.3)	(100.0)
Minor Arterial	28	1011	1141	2180
	(1.3)	(46.4)	(52.3)	(100.0)
Collector	36	929	783	1748
	(2.1)	(53.1)	(44.8)	(100.0)
Total	67	2531	3037	5635
	(1.2)	(44.9)	(53.9)	(100.0)

In so far as the entire highway network is concerned, the pavements in Indiana are in much better condition as compared to the nation's average present serviceability ratings (see Figures 1.1 and 1.2). These figures clearly show that the percent of miles deteriorated in both rural and urban interstate systems are less than the national average of 5.6 percent and 6.3 percent, respectively [14].

Traffic is a major factor which has been shown in the past to be significant in predicting the remaining life of pavements. The effect of accumulated traffic over time coupled with the effect of climate is very critical. Table 1.3 shows the Average Daily Traffic (ADT) distribution in Indiana as well as the national figures for the interstate rural system during 1981. It is interesting to note that over 95 percent of Indiana's rural interstate system carries an ADT in excess of 8,000 vpd. This value is quite high considering that only 57 percent of the total rural interstate system in the nation carries an ADT in excess of 8,000 vpd. The high levels of traffic in the aging interstate rural system in Indiana indicates that an immediate attention is needed in this segment of the Indiana highway system.

Furthermore, the effect of inflation coupled with the lack of adequate rehabilitation funds in the past to resurface in full those pavement sections already classified as

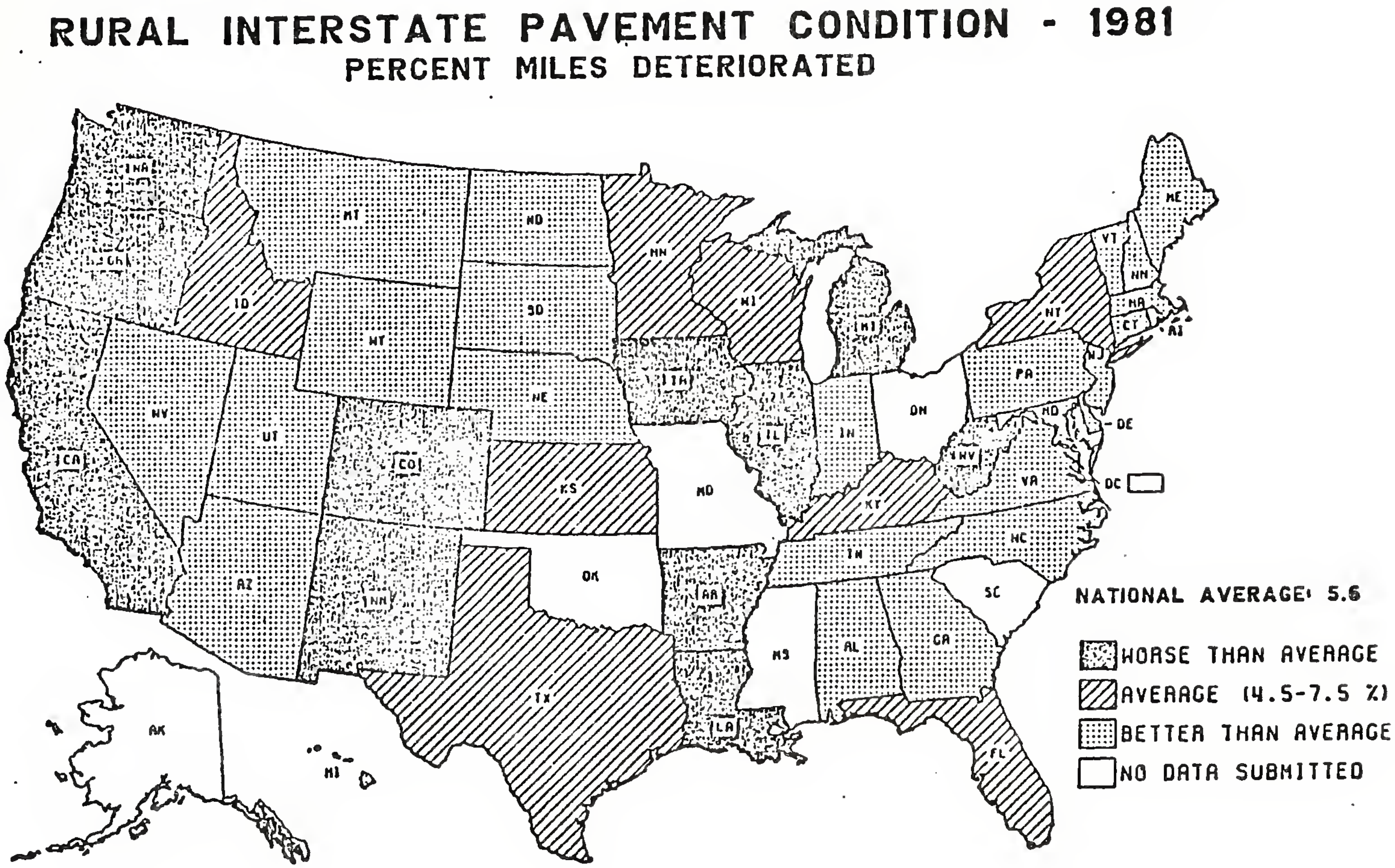


Figure 1.1 Percent of Miles Deteriorated in the Rural Interstate System as a Function of the National Averages During 1981. [14]

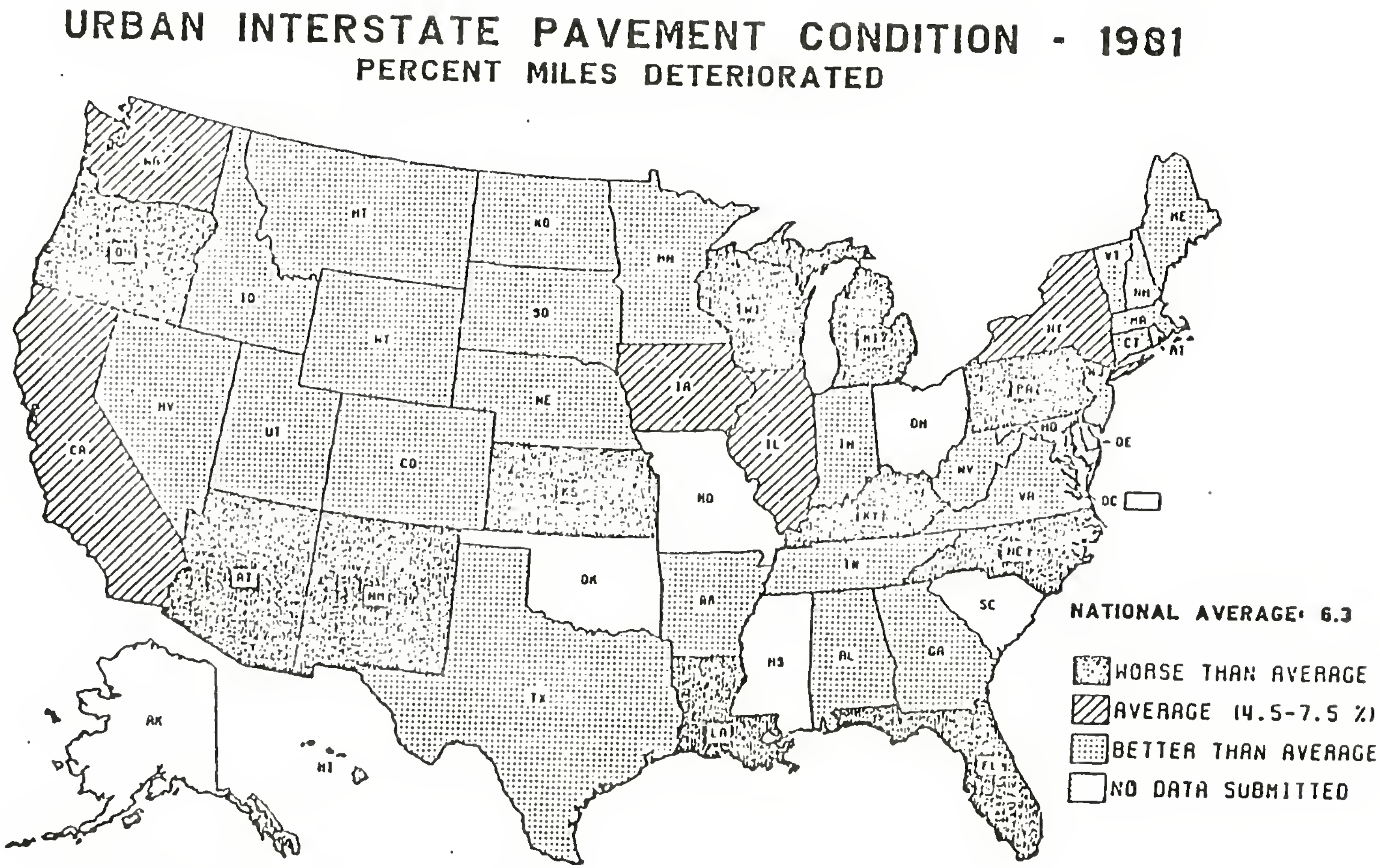


Figure 1.2 Percent of Miles Deteriorated in the Urban Interstate System as a Function of the National Averages During 1981. [14]

Table 1.3 Average Daily Traffic (ADT) Distribution in Indiana vs. the National Figures for the Interstate Rural System During 1981. [14]

ADT Range (vpd)	Indiana		National	
	Miles	Percent	Miles	Percent
< 8,000	41	4.8	11,896	43.1
8,000 - 19,999	564	66.0	12,073	43.6
> 20,000	250	29.2	3,663	13.3
Total	855	100.0	27,632	100.0

"poor" makes the situation even worse. This has been reflected dramatically in non-interstate pavements resurfacing projects in Indiana, particularly during the period of 1979 through 1983 (see Figure 1.3 (a)). In 1979 about 980 center-line miles were resurfaced in contrast to only 80 center-line miles rehabilitated in 1983, a reduction in mileage of almost 92 percent or 900 center-line miles [15]. In the interstate resurfacing program, on the other hand, the number of center-line miles resurfaced during the same period of time has been more or less constant, ranging between 45 to 55 center-line miles per year (see Figure 1.3(b)). This trend changed dramatically during calendar year 1983 since the number of miles resurfaced during this year increased over 100 percent as compared to 1982. The estimates for calendar year 1984 for both interstate and non-interstate resurfacing programs are encouraging.

In summary, even though the pavement network in the state of Indiana is in much better condition than the pavements in the nation as a whole and the budget estimates are expected to increase dramatically during the following years, there is still a need for developing a systematic procedure to allocate rehabilitation funds in a cost-effective manner.

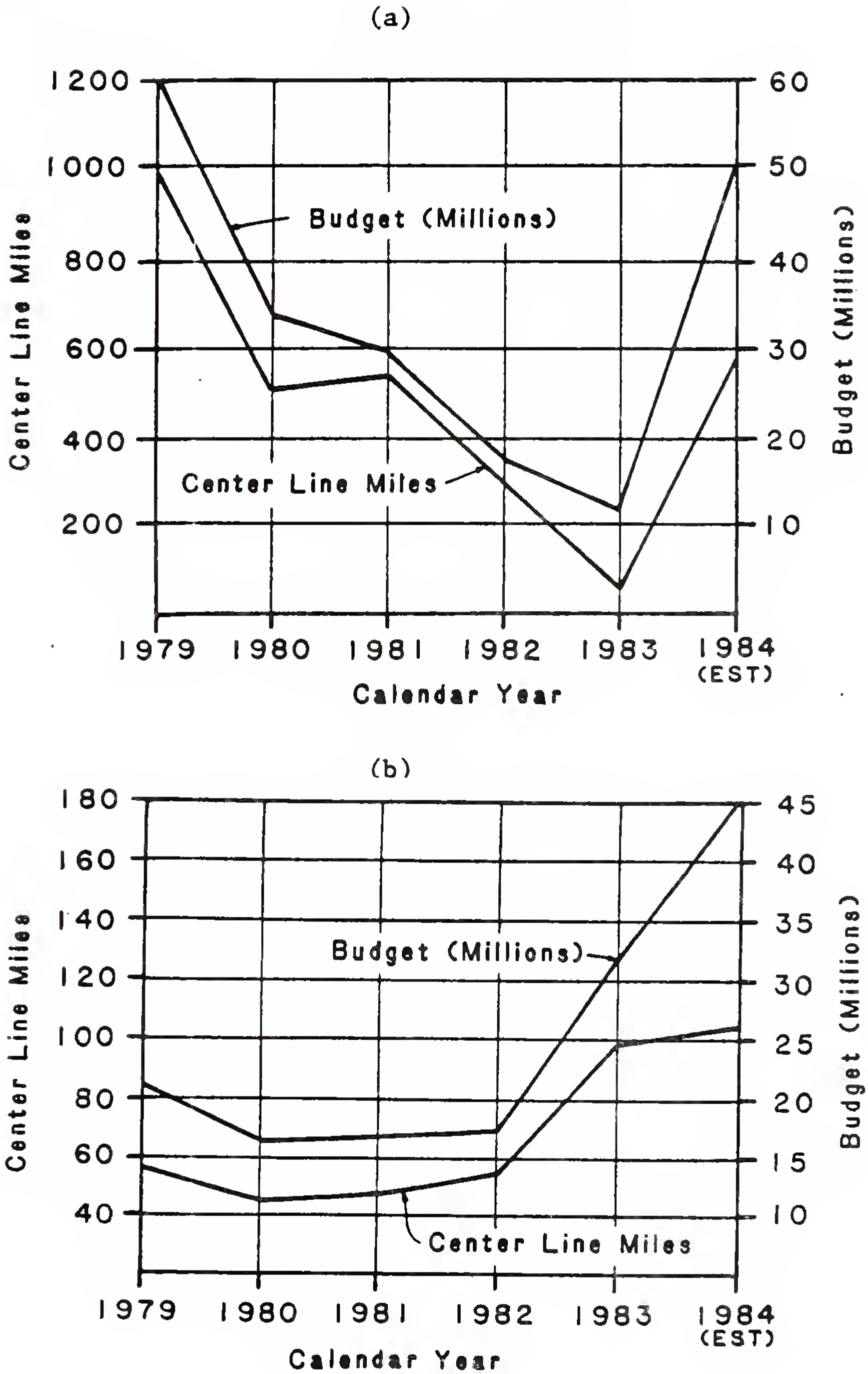


Figure 1.3 Center Line Miles and Budget Estimates for (a) Non-Interstate and (b) Interstate Resurfacing Programs in Indiana (1979-84). [15]

Purpose and Scope of the Study

The purpose of this research project is to develop a systematic procedure in terms of a mathematical model for allocating maintenance and rehabilitation funds to existing pavements within the state of Indiana. This procedure can be used by Indiana Department of Highways (IDOH) as part of its pavement management system. This work primarily documents efforts made to formulate two optimization models using a zero-one integer programming approach which is expected to lead to a more realistic and rational way of establishing candidate projects for major rehabilitation at the network level PMS.

In order to develop and implement the mathematical models, several tasks were performed:

1. Equivalent performance indices were developed for those performance factors which were felt to be the most significant in reflecting the current condition of pavement sections. Different indices were developed for different types of pavements (flexible, rigid, and CRC) and highway classes (interstate and state highways).

2. A performance function was developed to take into account the different types of rehabilitation strategies and the associated reduction in the overall

pavement distresses present in pavement section just prior to resurfacing.

3. Two pavement condition surveys were conducted. The first condition survey was performed on pavement sections located within the interstate system and previously classified as a "poor" section. The second survey was on pavement sections located within the Crawfordsville District to take into account the different distresses present on sections with different traffic distributions and different design criteria as compared to interstate pavements.

4. Two major computer programs were written. The first program was used to aggregate the skid and roughness inventories collected by the Research and Training Center (R&TC) during the years 1979 through 1982 into one master file which ultimately was used to select those sections which were classified as being in "poor" condition as input to the Optimization program. The second computer program was developed to generate the coefficients required for the optimization program. A listing of the second program is included in the appendix.

5. Regression equations for predicting future roughness as a function of the current roughness number were developed for each interstate route and pavement type combination.

6. An optimization program called LINDO (Linear Interactive and Discrete Optimizer) was adopted to run the mathematical formulations developed in this study.

Organization of the Report

The present report consists of eight chapters. Chapter 2 is a review of the current pavement management practices in the United States and abroad. Chapter 3 identifies the performance factors considered in this study and the criteria used for selecting them. Chapter 4 summarizes the results of the pavement condition surveys conducted as a part of this study. Chapter 5 describes the procedure used in the development of the performance function. The stochastic characteristics of roughness numbers are also introduced in this Chapter. Chapter 6 provides the details pertaining to the development and formulation of the optimization models. The application of the optimization models to the Indiana interstate highway network is covered in detail in Chapter 7. The conclusions and recommendations for further research in this area are outlined in Chapter 8.

There are five appendices to this report and they are included in Vol. III. Appendix A shows the geographic location of pavement sections surveyed during the pavement condition survey conducted in fall, 1982. Appendix B contains tables with the predicted roughness

numbers for the pavement sections located in the interstate system. A sample problem showing the application of the optimization program to the interstate highway network is presented in Appendix C. The results of the sensitivity analysis conducted on the budget is included in Appendix D. A listing of the computer program used to generate the coefficients for the optimization program is presented in Appendix E.

CHAPTER 2

LITERATURE REVIEW

Introduction

This chapter provides an overview of the pavement management programs currently used by some of the state highway departments across the nation. The benefits derived from implementing a pavement management system (PMS) as well as the major items required in implementing a PMS are described. The need for a pavement monitoring program and the key issues involved in establishing one are also addressed in this chapter. Indiana's status in implementing a pavement management system is also discussed. Finally, the optimization techniques used in existing PMS are reviewed.

Definition of Pavement Management System

Pavement management system (PMS) is a concept which involves the coordination, scheduling, and accomplishment of all activities performed by a highway agency in the process of providing adequate pavements for the road user [16,17,18,19,20]. Specifically, a PMS should assist decision-makers in determining optimal strategies for providing and maintaining pavements in a serviceable condition over a pre-determined period of time [21,22].

Pavement management is not a new concept. Management decisions are often made as part of normal operations every day in the state highway departments throughout the nation. These decisions, however, are generally judgmental and often are not based on objective data. In many cases, these decisions may lead to the choice of an alternative which may not be cost-effective in the long range. A rational PMS can improve the efficiency of the decision-making process by providing feedback information on pavement performance, pavement maintenance, pavement rehabilitation activities and the cost of providing and maintaining pavements. The ultimate goal of a PMS is therefore to achieve the best use possible for the public funds allocated to pavement maintenance and rehabilitation.

Most of the pavement management activities are classified into two administrative levels, namely the network and the project level. At the network level the decisions are made for a group of projects or for an entire network such as the interstate system or the state highway system. At the project level the primary concern is a specific maintenance type for a section of highway.

Major Items in Implementing a PMS

Pedigo and Hudson [19,22,23] have outlined a series of items which must be considered in the successful implementation of a pavement management system. These are:

1. Decision to start
2. Preparation of goals, objectives, and preliminary budget
3. Commitment from top management
4. Preliminary work plan and formation of technical group
5. Establishment of a steering committee
6. Development of a detailed work plan
7. Evaluation of hardware and software needs
8. Development of a preliminary system both at the network and project level
9. Testing and verification of the preliminary system
10. Demonstration of the second-stage system
11. Locate PMS activity in organizational structure
12. Acceptance of the PMS for implementation on a full scale basis
13. Routine operation of the system
14. Improvement and maintenance of the PMS

Although there are numerous items that need to be considered in implementing a complete pavement management system, it is generally agreed that full support by top management officials and the decision to start to develop the system are the most important items. It is not necessary to

develop the complete system all at one time. After the system is initiated, it can be modified and updated while it continues to provide useful data for decision-making.

Need for a Pavement Monitoring Program

In order to implement an efficient pavement management program, it is essential to establish a formal monitoring system. Lytton, et al. [24] have outlined some of the key issues and benefits involved in establishing a long-term pavement monitoring program. These are summarized below:

1. A need to identify specific data elements to collect,how to measure them, which equipment to use, the frequency of measurement both over time and within a network and project, the method of storage and retrieval of data, and how to analyze and evaluate the data.

2. A firm commitment for continued support from the decision-makers is essential.

3. A need to use carefully planned sampling surveys and regression equations to reduce the data collection effort to a minimum.

4. An effective pavement monitoring program can provide the required data for cost-allocation studies, for analyzing pavement deterioration rates and to access the relative damage attributable to traffic and environmental factors, and determination of the optimum time to rehabilitate.

5. A management program must use optimization techniques to ensure the most cost-effective funding and timing strategies are used on each pavement section in the network.

6. A long term pavement monitoring program can pay for itself only if it is integrated into an overall statewide pavement management process.

The scope of the present research project is aimed toward item 5, the development of an optimization model to be used as part of Indiana's pavement management system.

The following sections describe the available pavement management systems and current pavement management practices used by several state and provincial highway departments.

Current Pavement Management Techniques

Alberta

Alberta Transportation developed the Pavement Information and Needs System (PINS) as part of their efforts in implementing a pavement management system in the province of Alberta, Canada [25].

PINS has several modules, these include a series of performance prediction models and various data processing and analysis programs which take the individual field measurements and calculate performance measures such as the Pavement Quality Index (PQI), Riding Comfort Index (RCI), Structural Adequacy Index (SAI), and Visual Condition Index (VCI) which are then used as input to the performance prediction models which then assist decision-makers in identifying present and future needs.

PINS is not a complete PMS since it does not have the capability to optimize the present and future needs. On the other hand, it does have the capability of ranking the sections in the order of their improvement needs and in terms of the performance parameters.

Arizona

The Arizona Department of Transportation has recently implemented a pavement management system that consists of three phases [5,26,27,28]:

I. Development of models to optimize the design of new construction and major maintenance

II. Verification of models with actual data and the creation of a computerized data base

III. Development of a network optimization system (NOS)

The heart of Arizona's PMS is the Network Optimization System (NOS) developed during phase III. The optimization model used by NOS is based on the formulation as a Markovian decision process and converted to a linear programming model. Six performance factors are used as input to the optimization algorithm. These are:

1. average daily traffic, ADT (3 levels)
2. regional factor (3 levels)
3. index to first crack (5 levels)
4. present roughness (3 levels)

5. present amount of cracking (3 levels)
6. change in amount of cracking during the previous year (3 levels)

Seventeen rehabilitation actions including routine maintenance are considered by NOS for asphalt pavements and two rehabilitation actions for concrete pavements.

Another important input factor to the NOS program is the set of transition probabilities associated to each road category. A transition probability is defined by ADOT as the proportion of roads in condition i that moves to condition j in one year if the k^{th} rehabilitation action is applied. Arizona developed the transition probabilities from regression equations developed from a sample of pavement performance data from their network.

California

The California Department of Transportation (CALTRANS) has developed and implemented a PMS which emphasizes an organized approach to pavement rehabilitation, and a structural systems approach for the management of existing pavements [6,29]. CALTRANS's PMS is divided into six major stages. First, an inventory is made of the existing pavement condition. Second, the extent and severity of the pavement condition is measured. Third, appropriate maintenance repair strategies are identified. Fourth, cost-effective

strategies and feasible alternatives for candidate projects are identified. Fifth, maintenance strategies are related to the corresponding CALTRANS highway program structure. Sixth, candidate projects for each CALTRANS highway program component within each Transportation District are organized on a statewide basis as well as for other regional groupings.

CALTRANS has also developed rating systems for both flexible and rigid pavements. The severity and extent of each pavement distress are taken into consideration in the selection of the proper rehabilitation strategy (see Figures 2.1 through 2.4). Thus the primary function of CALTRANS PMS is to correlate pavement problems with feasible maintenance strategies. The condition survey is scheduled once every two years.

Colorado

The city of Arvada in Colorado has developed a computer program for their pavement evaluation and management system (PMS) which relies heavily on the pavement condition rating and the ADT [30].

The pavement rating score is computed by deducting points from an initial score of 100 based on the extent and severity of the different types of pavement distress and

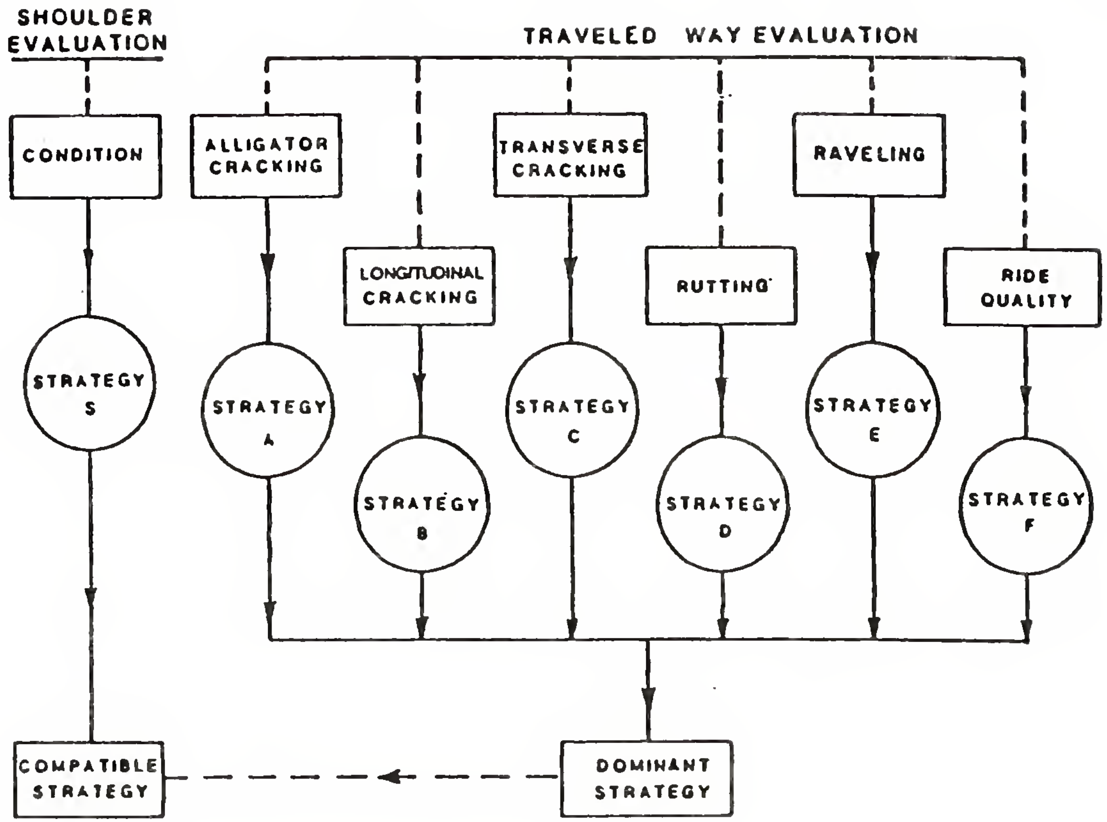


Figure 2.1 CALTRANS Flexible Pavement Condition Evaluation Procedure. [29]

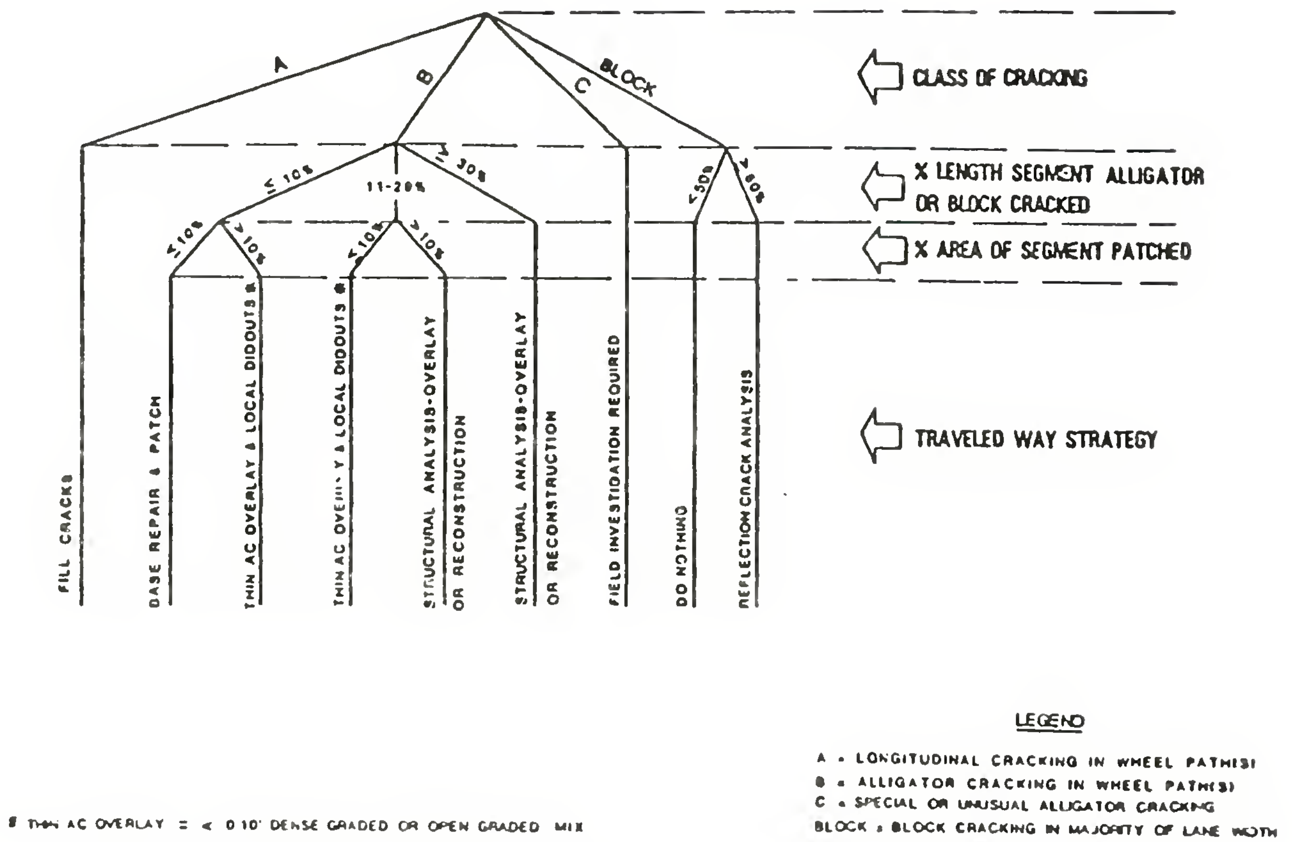


Figure 2.2 CALTRANS Flexible Pavement Alligator/Block Cracking Rehabilitation Decision Tree. [29]

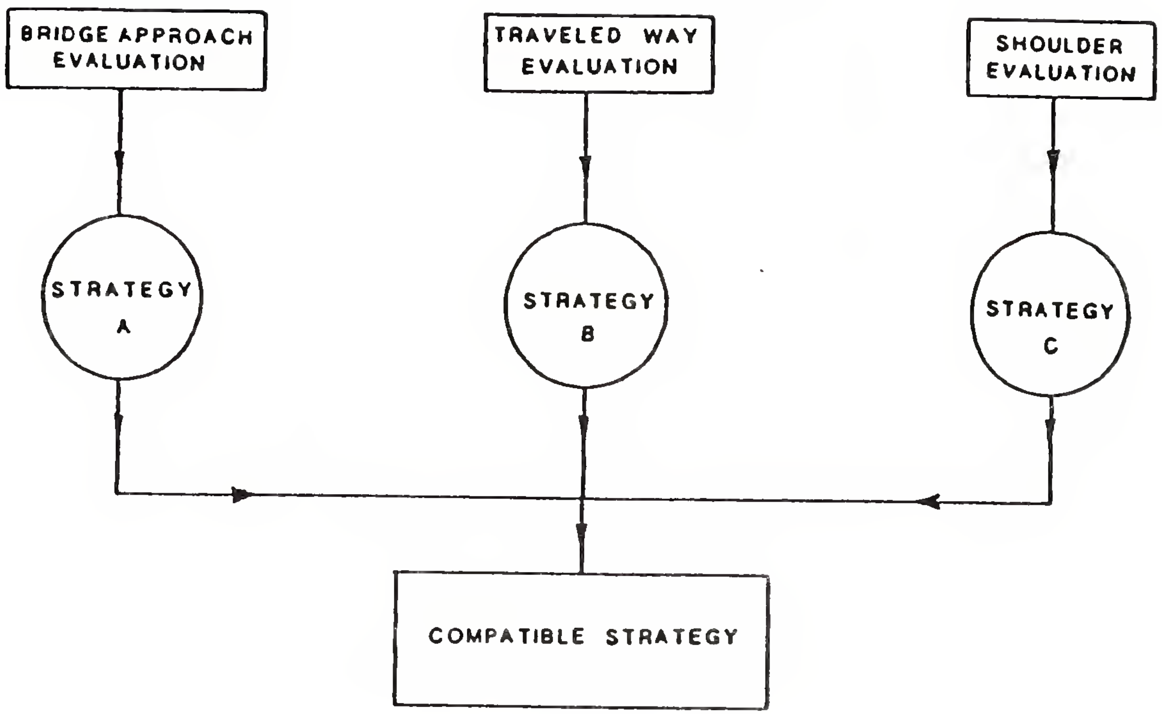
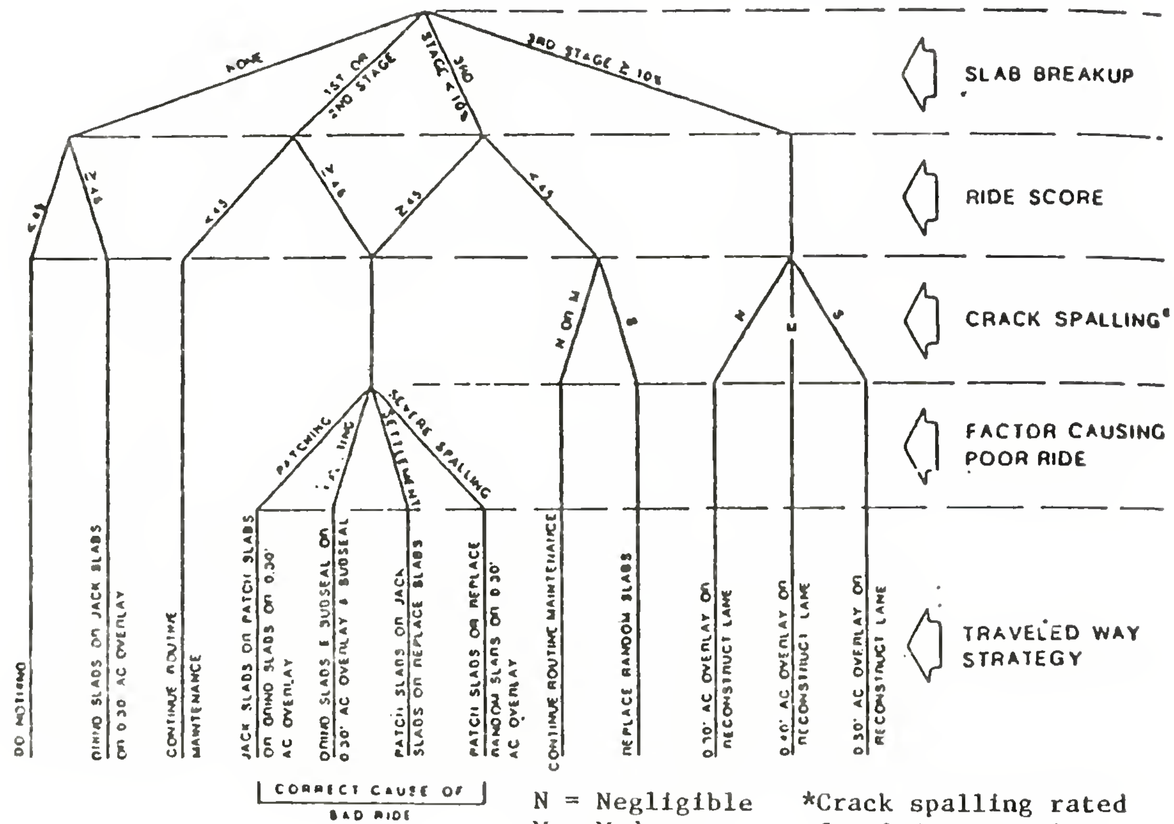


Figure 2.3 CALTRANS Rigid Pavement Condition Evaluation Procedure. [29]



N = Negligible
M = Moderate
S = Severe

*Crack spalling rated for 3rd stage slab breakup only

Figure 2.4 CALTRANS Rigid Pavement Traveled-Way Rehabilitation Decision Tree. [29]

ride quality. The equation used is as follows:

$$PRS = 100 - D \tag{2.1}$$

where:

PRS = pavement rating score;

D = summation of the individual deduct value for the various distress observed.

The rehabilitation procedure is based on the extent and severity of the existing distresses present and the amount of traffic carried by the facility. The procedure is very similar to the one developed in California [6,29].

An empirical equation is used to produce priority lists and is as shown below:

$$P = (C/L) \left[\frac{\sqrt{ADT}}{CI}\right] [F] \tag{2.2}$$

where:

C = cost of the specific rehabilitation alternative chosen as appropriate for a specific section;
L = length of the pavement to be rehabilitated;
ADT = average daily traffic;
CI = pavement condition rating index score;
F = 1.0 if street is not industrial or a bus route, 1.1 if street is an industrial classification or a bus route;
P = priority index.

Pavements with the highest value of P are those which in most cases will have the highest cost with respect to the length of the section to be rehabilitated and will also be in a poor condition as indicated by the condition rating score.

Construction Engineering Research Laboratory, U.S. Army

The U.S. Army Construction Engineering Research Laboratory (CERL) has developed a computerized pavement maintenance and management system called PAVER [31,32]. The computer program relies heavily on the Pavement Condition Index (PCI) and the deduct curves which were originally developed for airfield pavements and military installations [33,34]. PAVER consists primarily of a data base (see Figure 2.5) and a set of report generator programs. The PAVER computer program, in its present format, considers roughness and skid resistance in a subjective manner. The program does not take into account deflection measurements, and therefore, there is no subroutine to design overlays based on deflections.

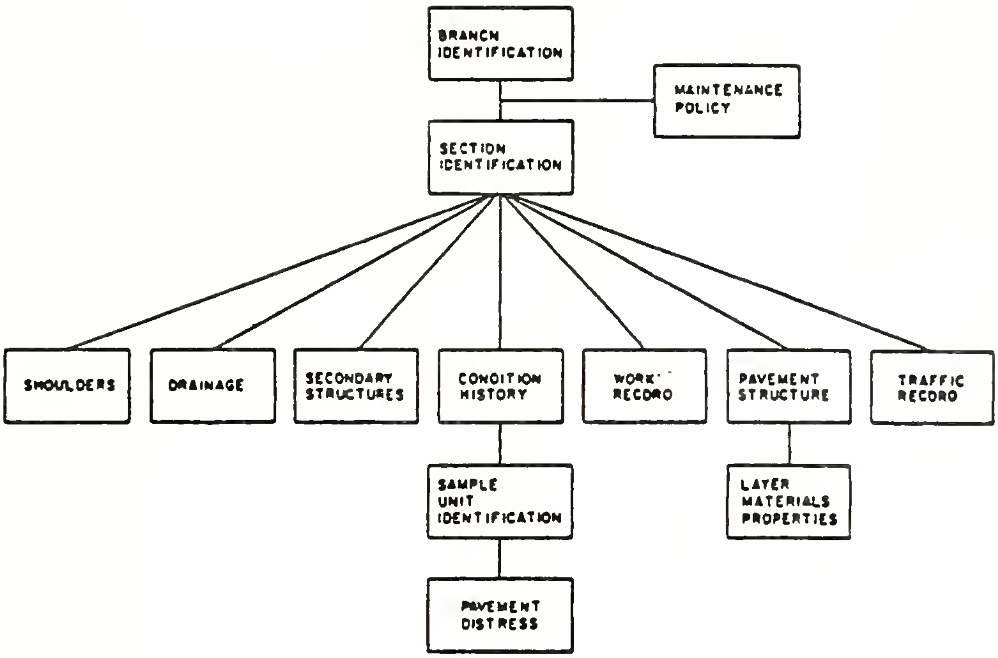


Figure 2.5 Structure of PAVER Data Base. [31].

Denmark

The Danish pavement maintenance and rehabilitation management system (DMS) as reported by Ullidtz [35] consists of four steps:

1. Inventory of existing pavement network (riding quality, structural adequacy, etc.)
2. Benefit/Cost Analysis
3. Optimization
4. Consequence Analysis

Of primary interest is the optimization phase. First, the solutions of each sub-section are ranked according to decreasing benefit/cost ratios and uneconomical solutions are discarded, and the optimization model is then applied. The problem is formulated as a 0-1 integer programming (IP) model using a heuristic procedure suggested by Mahoney et al [36]. The procedure finds solutions very close to the continuous optimal linear programming solution. The IP solution is the combination of maintenance strategies which will result in the maximum benefit obtainable with the available budget. The model has the capability to generate information for three to five years into the future.

Florida

The Florida Department of Transportation developed a pavement management system to assist decision makers in the

process of allocating funds for rehabilitation [8,37,38]. In this system, highways are evaluated on the basis of their engineering rating (ER). The engineering rating (ER) is a combination of the operational or ride rating (OR), which is a measure of the roadway ability to handle traffic, and the structural or distress rating (SR), which is a measure of the roadways structural condition. The equation used to compute the ER is shown below:

$$ER = \sqrt{OR \times SR} \qquad (2.3)$$

The change in engineering rating (ΔER) is computed for each pavement section under a given maintenance strategy along with the resulting cost-effectiveness (CE) index for the strategy. The CE index is represented by:

$$CE = \frac{\Delta ER \times ADT \times LENGTH}{\text{Present Worth Dollars}} \qquad (2.4)$$

Based on these three terms, those projects having the lowest initial ER, highest ΔER and largest CE value will be assigned the highest priority. The resultant is adjusted to a value from 1 to 100 to indicate the priority with respect to all other projects in consideration.

The available funds are then allocated to the six highway districts by program category and year. The district then selects projects for each of the 25 program categories

using the priority lists as a starting point.

The friction number is not considered in the initial phase of priority setting, but is handled separately.

Idaho

The Idaho Transportation Department (IDT) has developed a pavement management system which essentially is a modification of Utah's Pavement Performance Management Information System (PPMIS). The system begins with a comprehensive inventory of structural adequacy, pavement riding quality, surface distress and skid resistance [13,39,40]. Each of these measurements is converted to an index ranging from 0 (very poor) to 5 (very good). The pavement sections are then ranked on the basis of a final index which is a weighted average of the structural (deflection), cracking (distress), and PSI (roughness) indices. The index also takes into account different traffic levels as well as the functional classification of the highway. The final index (FI) is calculated using the following equation:

$$FI = 0.47\ [F_1(PSI)^{1.5} + F_2(SI)^{1.5} + F_3(DI)^{1.5}] \quad (2.5)$$

where:

PSI = Present serviceability index;

SI = structural index;

DI = distress index;

F_1, F_2, F_3 = weighting functions that take into account traffic and highway functional classification.

The final index along with the other indices are used to produce priority list of needs, both in the form of summary tables as well as graphs.

The program has also the capability for overlay design. The graphs and summary tables are directed to assist decision makers at the network level while the overlay design subroutine assists in decisions at the individual project level.

The analysis performed in PPMIS does not consider the optimality of network improvements. Therefore, the program cannot be considered a complete pavement management system.

Illinois

The University of Illinois has developed a computerized system for state and nationwide evaluation of portland cement concrete (PCC) pavements [41,42]. The objectives of the COncrete Pavement Evaluation System (COPES) is to provide a procedure to periodically collect and evaluate data from in-service concrete pavements.

COPES was developed to include three conventional types of pavements: jointed plain concrete pavements (JPCP), jointed reinforced concrete pavements (JRCP), and continuously reinforced concrete pavements (CRCP). COPES concentrates on distress as the primary indicator used in improving design, construction, and maintenance procedures, although other performance indicators such as roughness, pavement serviceability, structural non- destructive testing (NDT), and skid resistance are also included in the system. These performance indicators are considered in the determination of rehabilitation needs.

COPES, however, is not a complete pavement management system (PMS), nor is it a maintenance management system (MMS). However, it provides an excellent basis upon which to develop a comprehensive pavement management system.

New York

New York Department of Transportation's effort in establishing a pavement management system has been aimed at the identification of deficient pavement sections [9]. To accomplish this task, a graphical representation of the pavement surface profile versus milepost number is constructed from the data collected during the monitoring phase. The area under the curve is integrated and then averaged for the pavement section being considered in order

to characterize the energy disturbance present at the running speed. The resulting value, termed the "E-value", is calibrated and then correlated with the present rideability index (PRI) which in turn is determined by a panel rating. Minimum acceptable rating values are used to identify "candidate" and "essential" projects.

Ohio

The Ohio Department of Transportation (ODOT) developed a Pavement Maintenance Management System (PMMS) which includes four primary components [12,43,44]:

1. Development of network monitoring criteria, including monitoring parameters (i.e. skid number, deflection, roughness, and visual distress), maintenance-needs indicators or "trigger values", present serviceability index(PSI) and friction number testing requirements and deterioration rates.

2. A pavement condition rating(PCR) system, including a system for rating visual distress, field verification of the PCR, and identification of the need for structural investigation.

3. A system for determining project priorities and selecting the optimal repair method, including prioritization based on condition, formulation of maintenance alternatives and economic analysis, and selection of optimal maintenance alternatives, and

4. Establishment of new data banks such as a pavement section files, pavement condition files, and the priority maintenance file.

The most important aspect of the Ohio PMMS is the method of establishing priorities. The parameters which are used by Ohio to establish maintenance priorities are

roughness (PSI), friction number (FN), and pavement distress (PCR). At the present time pavement distress is considered the most important in the priority system while roughness and friction number are of lesser importance. Traffic is considered in the priority system primarily in urban districts.

Ontario

The Ontario Ministry of Transportation and Communications has developed a rating procedure to determine the priority of rehabilitation needs [45,46,47,48,49]. The rating procedure combines the riding quality of the pavement with the type, severity, and extent of the pavement distresses. The Riding Comfort Rating (RCR) is a subjective rating of riding quality which ranges from 0-10.

Riding quality is measured at 50 mph and is judged by the same rating team which performs the condition survey. User's manuals including standard rating forms have been prepared for the two types of pavements. Guidelines are presented in the user's manual to assist the rater in assigning a Pavement Condition Rating to the pavement section in question (see Table 2.1).

An alternative method called the Distress Index (DI) has also been developed. This method combines both the

Alternative	Rating	Pavement Current Condition
Reconstruct pavement within 2 years	0-20	Pavement is in poor to very poor condition with extensive severe cracking, alligatoring and dishing. Rideability is poor and the surface is very rough and uneven.
Reconstruct pavement in 2 to 3 years	20-30	Pavement is in poor condition with moderate alligatoring and extensive severe cracking and dishing. Rideability is poor and the surface is very rough and uneven.
Reconstruct pavement in 3 to 4 years	30-40	Pavement is in poor to fair condition with frequent moderate alligatoring and extensive moderate cracking and dishing. Rideability is poor to fair and surface is moderately rough and uneven.
Reconstruct pavement in 4 to 5 years or resurface within 2 years with extensive padding	40-50	Pavement is in poor to fair condition with frequent moderate cracking and dishing, and intermittent moderate alligatoring. Pideability is poor to fair and surface is moderately rough and uneven.
Resurface pavement in 3 years	50-65	Pavement is in fair condition with intermittent moderate and frequent slight cracking, and with intermittent slight or moderate alligatoring and dishing. Rideability is fair and surface is slightly rough and uneven.
Resurface pavement in 3 to 5 years	65-75	Pavement is in fairly good condition with frequent slight cracking, slight or very slight dishing and few areas of slight alligatoring. Rideability is fairly good with intermittent rough and uneven sections.
Routine Maintenance	75-90	Pavement is in good condition with frequent very slight cracks. Rideability is good with few slightly rough and uneven sections.
No Maintenace Required	90-100	Pavement is in excellent condition with few cracks. Rideability is excellent with few areas of slight distortion.

Table 2.1 Ontario's Guidelines for Estimating Pavement Condition Rating for Flexible Pavements. [46]

riding comfort (RCR) and distress manifestations (DM) into one composite equation [49].

Pennsylvania

The Pennsylvania Department of Transportation uses the Mays Ride Meter to compute the present serviceability index (PSI). This value is compared with a Terminal Serviceability Index (TSI) to decide whether or not a corrective action is required [50,51]. The TSI values were determined from the PSI distributions corresponding to each of the highway functional classification. The PSI value which was exceeded 95 percent of the time was taken as the TSI. The TSI values for each of the five functional classification of highways used by Pennsylvania DOT are shown in Table 2.2.

The Road Rater is used to evaluate the structural adequacy(i.e. overlay thickness requirements) of those pavement sections which has a PSI below the TSI for its functional classification.

South Dakota DOT

The South Dakota Department of Transportation (SDDOT) has developed a methodology which uses a weighted factor approach, for setting priorities among resurfacing projects [92]. A list which contains all the possible elements that

Table 2.2 Terminal Serviceability Indices (TSI) Used by the Pennsylvania Department of Transportation . [50]

Highway Functional Classification	TSI
Interstate	3.30
Principal Arterial	3.20
Minor Arterial	3.00
Collector Roads	2.50
Local Access	2.20

can affect the performance of the pavement structure is first developed. An importance value curve is then developed for each element in order to convert all objective measurements of each element into a standard scale of 0 to 10. Each element is assigned a priority ranking weight based on experience and on the immediate needs of the agency (see Table 2.3). A priority ranking value is calculated for each candidate resurfacing project by summing the products of the importance value and the priority ranking weights for all the elements. The importance value curves have been adjusted to take into account different traffic volume levels as well as the functional classification of the highway segment in question.

Texas

The Texas Department of Highways and Public Transportation developed a visual examination procedure to evaluate and establish maintenance priorities [52]. Different visual examinations and rating procedures are used for pavement, shoulder, roadside and drainage features, and traffic services. The pavement condition rating is computed by subtracting deduct values related to the different types of pavement distresses from 100. A deduction to take into account the PSI of the pavement section is also included in the pavement condition rating. A user's manual has been

Table 2.3 South Dakota's Priority Ranking Evaluation Worksheet. [92]

Highway: Location: F. A. System: Length:

Segment (1)	Segment Weight (2)	Category (3)	Category Weight (4)	Element (5)	Element Factor (6)	Importance Value (7)	Element Weighted Factor 2x6x7=(8)	Priority Ranking Value (9)
Engr.	(100%)	Condition	(81%)	Roadway Strength	.04	0 1 2 3 4 5 6 7 8 9 10		
				Drainage Adequacy	.07	0 5 10		
				Surface Condition	.25	0 1 2 3 4 5 6 7 8 9 10		
				Rem. Surface Life	.22	0 1 2 3 4 5 6 7 8 9 10		
				Rideability	.23	0 1 2 3 4 5 6 7 8 9 10		
		Geometrics	(05%)	Roadway Width	.00	0 1 3 6 8 9 10		
				Shoulder Width	.00	0 1 3 6 9 10		
				Surface Width	.00	0 1 2 3 4 6 8 10		
				Gradient	.00	0 1 2 3 4 5 6 7 8 9 10		
				Curvature	.00	0 1 2 3 4 5 6 7 8 9 10		
				Sight Distance	.00	0 1 2 3 4 5 6 7 8 9 10		
				Surface Thickness	.05	0 1 2 3 4 5 6 7 8 9 10		
		Traffic	(06%)	Current Traffic	.03	0 1 2 3 4 5 6 7 8 9 10		
				Truck Traffic	.03	0 1 2 3 4 5 6 7 8 9 10		
				20-Yr Traffic Growth	.00	0 1 2 3 4 5 6 7 8 9 10		
				Vol/Capacity Ratio	.00	0 1 2 3 4 5 6 7 8 9 10		
		Maintenance	(05%)	Surface Maintenance	.05	0 1 2 3 4 5 6 7 8 9 10		
		Safety	(03%)	Friction	.05	1 2 3 4 5 6 7 8 9 10		
				Accident Rate	.00	0 1 2 3 4 5 6 7 8 9 10		

prepared to be followed by the rating team which describes the different types of distresses as well as the method to establish the extent and severity of them.

A computer model called PRP01 has been developed recently by Gutierrez and McCullough [53] to schedule rehabilitation of rigid pavements in Texas within a certain period of time. The input data are condition survey information of a set of rigid pavements for the same year. The solution is obtained using distress models, i.e., distress indices and distress prediction equations.

Utah

The Utah Department of Transportation collects four types of information in order to asses the current condition of the pavement structure. These are [11,54,55,56]:

1. Present Serviceability Index (PSI) using the Mays Roadmeter
2. Pavement Distress based upon visual survey
3. Structural Adequacy using the Dynaflect deflection measurements
4. Friction Number using the Mu Meter

Pavement distress and structural adequacy are quantified in terms of an index between 0 and 5 in order to have the same units as the PSI measurements. The average of these three values is then computed for each section. In

those sections where the ADT is very high, the PSI is weighted more heavily to account for user costs. If the truck traffic is high, then the structural adequacy is weighted more heavily.

The overall index is then used to prepare priority listings which are then distributed to district offices, as well as to the planning and programming sections. This information is used to determine types and timing of required improvements, the degree to which corrections are needed, and the overall priority ratings of the proposed improvement. Three categories of rehabilitation projects are identified using the listing combined with judgment of the district directors. The first category includes those pavement sections which must be done immediately. The second category consists of those which can afford to be delayed. The third category refers to those sections which are in need of significant reconstruction (severe geometric problems as well as pavement distresses).

Washington

The Washington State Department of Transportation (WSDOT) developed a pavement management system for both the project and network levels over a period of five years [10,57,58].

The system has essentially four major components:

1. Master File
2. Interpreting Program
3. Project-Level Optimizing Program
4. Network-Level Program

The Master file is essentially the heart of the system. It uses the milepost limits of the most recent paving contracts as the common denominator to combine information from five existing data files, namely:

1. Road Life Data
2. Geometric Data
3. Traffic Data
4. Friction Data
5. Pavement Condition and Roughness Data

The Interpreting program fits performance curves to the ratings to predict future pavement performance and the potential time of rehabilitation.

The Project-Level Optimizing Program utilizes the performance equations developed by the interpreting program to establish the most cost-effective rehabilitation strategy for each project.

The Network-Level program is actually a summarizing program which combines the performance of existing projects as analyzed by the interpreting program, and recommended

time of rehabilitation as determined by the project-level optimizing program, to establish a six-year rehabilitation program.

At the present time, WSDOT is using the performance curves produced by the interpreting program to set priorities among pavement sections for rehabilitation. The output of the project-level optimizing program and network-level program are used by the highway districts as guidelines in preparing future rehabilitation programs.

Existing Pavement Evaluation Methods

Most of the highway agencies that have implemented pavement management programs collect one of the following four types of data to assist decision makers in establishing maintenance and rehabilitation needs:

1. Roughness (riding quality)
2. Surface distress
3. Structural evaluation (surface deflection)
4. Skid resistance (surface friction)

The following paragraphs summarize the most important features regarding the above factors for those agencies which have implemented a pavement management system.

Roughness and Riding Quality

In Table 2.4 a summary is presented of the procedures used by highway agencies to measure roughness. With the exception of New York and Ontario, all other agencies use a ride meter (i.e. PCA or Mays roadmeter) to measure pavement roughness. New York has developed an electronic device to measure pavement surface profile and Ontario uses a subjective rating procedure to assess the riding quality of pavements.

Surface Distress

In Table 2.5 a summary is presented of the procedures used by highway agencies to evaluate pavement surface condition. In summary, most of the highway agencies divide the network into small segments, one-mile increments being the most commonly used. Cracking, rutting, and patching are the pavement distresses most commonly evaluated. The extent of the pavement condition surveys depends upon the size of the network in question. One to two year frequency is most common.

Pennsylvania and New York do not conduct pavement condition surveys on a routine basis, however, they occasionally spot check selected projects.

Table 2.4 Summary of Methods Used by Agencies to Measure Roughness

Agency	Comments
Arizona	- Mays ride meter used to rate annually. Panel rating - used to develop a Rideability Index that is different - from PSI.
California	- Use PCA ride meter, but ride score is not part of - pavement distress evaluation.
CERL	- Roughness is considered in a subjective manner
Florida	- Mays ride meter correlated to CHLOE profilometer. - Determine Ride Rating (RR) based on calibration for - each vehicle.
Idaho	- Cox (PCA) road meter is used for each mile and converted - to present serviceability index (PSI)
Illinois (COPES)	- Roughness is considered in a subjective manner -
Kentucky	- Use G.M. Profilometer as well as a ride meter. - Ride meter used for ride quality correlation. Roughness - Index (RI) correlated to PSI based on contract length.
New York	- Unique mobile vehicle response profiler which is very - sensitive. Entire system is monitored annually.
Ohio	- Mays meter is used to collect roughness data, but is not - used for routine monitoring.
Ontario	- Subjective rating of ride. Determine Riding Comfort - Index (RCI).
Pennsylvania	- Mays road meter is used to rate the network annually. - All data tied to G.M. profilometer previously used.
Texas	- Mays road meter correlated with Surface Dynamics - Profilometer on 0.2 mile sections on an annual basis.
Utah	- Cox (PCA) road meter on one mile increments. Roughness - reported in terms of present serviceability index (PSI)
Washington	- Cox (PCA) road meter on all sections and ride score is - is used as part of overall rating.

Table 2.5 Summary of Methods Used by Agencies to Evaluate Surface Condition

Agency	Comments
Arizona	- Crack survey is primary evaluation using standard photos
California	- Structural defects such as cracking, rutting, etc. are - rated for extent and severity annually for interstate, - 3 to 4 years min. of others. Different rating method - for flexible and rigid pavements.
CERL	- The Pavement Condition Index (PCI), which is based on - deduct values, is used to evaluate surface condition. - The rating method takes into account the extent and - severity of all pavement distresses.
Idaho	- Photographs similar to Arizona, are used to evaluate - the condition of the pavement surface. Condition survey - conducted on 2 to 3 year cycles.
Illinois (COPES)	- The Pavement Condition Index (PCI), which is based on - deduct values, is used to evaluate surface condition. - The rating method takes into account the extent and - severity of all pavement distresses.
Kentucky	- Use surface condition rating as feedback for design - deficiencies rather than routine monitoring.
New York	- None made routinely
Ohio	- Based on the Pavement Condition Rating (PCR) which is a - numerical index reflecting the composite effects of - varying distress types, severity, and extent. Based on - the deduct value concept.
Ontario	- Pavement Condition Rating, PCR determined by rater as - set forth in manuals. One or two year frequency. Ride - and distress combined to determine Distress Index, DI.
Pennsylvania	- Not made at present
Texas	- Structural defects measured objectively based on visual - rating. Vehicle mounted camera provides basis for dis- -tress rating on candidate projects only.
Utah	- Detailed evaluation of cracking, rutting, patching, etc - on 500 ft. of one mile sections made by photologging. - Both subjective and objective analysis are used.
Washington	- Structural defects such as cracking and rutting are - measured every other year on a subjective basis. - A 200 ft. of one mile section is evaluated.

Structural Evaluation-Deflection

In Table 2.6 a summary of the procedures used by highway agencies to measure structural adequacy is presented. In summary, most of the highway agencies measure deflection by using the dynaflect, road rater, or benkelman beam. However, only the state of Utah measures deflection on a routine basis. The common practice is to measure deflections at specified or selected locations, usually at critical sections as detected by other measurements such as roughness, pavement condition survey, and so on. These pavement sections are, in most cases, candidates for reconstruction, therefore the deflection measurements are primarily used to establish overlay requirements.

Skid Resistance (Surface Friction)

In Table 2.7 a summary of procedures used by highway agencies to measure surface friction is presented. All the states measure surface friction either by using the ASTM skid trailer or the Mu Meter. The frequency of testing depends upon the size of the network, but most states measure the entire system annually to every three years. Even though most states measure surface friction on a routine basis, they do not consider these data in their initial priority setting procedure. Instead, this information

Table 2.6 Summary of Methods Used by Agencies to Measure Structural Adequacy

Agency	Comments
Arizona	- Dynaflect deflections at three locations per mile, - but not used for routine monitoring.
California	- Dynaflect deflections used in design but not for - routine monitoring.
CERL	- Does not take into account deflection measurements
Florida	- Does not take deflections into account.
Idaho	- Dynaflect is used to measure deflections. For network - survey two deflections measurements per mile. For over- - lay design purposes, 10 tests per mile on selected - sections.
Illinois (COPES)	- Deflection measurements can be incorporated using any - type of non-destructive testing (NDT) device.
Kentucky	- Road rater deflections at specific locations for - design evaluation only and not for routine monitoring.
New York	- Does not take deflections into account.
Ohio	- Dynaflect is used to measure deflections, but not on a - routine basis.
Ontario	- Dynaflect deflections measured at random locations - for pavement sections in need of rehabilitation.
Pennsylvania	- Road rater deflections used to evaluate selected - sections which have reached terminal serviceability
Texas	- Dynaflect deflections measured at critical locations - only and not for routine monitoring.
Utah	- Dynaflect deflection measurements used to predict - remaining life based on projected 18-kip loads. One - test per mile with temperature corrections. Measured - on candidate projects only.
Washington	- Benkelman beam is used to measure deflections for - selected locations, but not used for routine monitoring

Table 2.7 Summary of Methods Used by Agencies to Measure Surface Friction

Agency	Comments
Arizona	- Mu meter used for 500-ft. section within each mile - for the entire system on an annual basis
California	- ASTM skid trailer is used periodically.
CERL	- Skid resistance is considered in a subjective manner.
Florida	- ASTM Skid trailer is used to measure skid resistance, - however, is measured as part of a separate system.
Idaho	- Mu meter and ASTM skid trailer are used. Skid trailer is - currently used, one test at each milepost for the entire - system annually.
Illinois (COPES)	- Skid resistance in taken in a subjective manner, but it can - incorporate measurements made with skid trailer.
Kentucky	- ASTM Skid trailer.
New York	- ASTM Skid trailer covers entire system about every - three years. Test every 0.1 mile or 0.2 mile. Data is - a separate system used primarily for accident surveilance.
Ohio	- Skid trailer is used on an annual basis on the Interstate - and Primary System with the secondary system on a two to - three year cycle. Pavement sections having high incidence - of accident are tested on a more concentrated sampling.
Ontario	- Information was not available.
Pennsylvania	- ASTM skid trailer.
Texas	- ASTM skid trailer is used to test entire network annually.
Utah	- Mu meter is used on wet pavement. A 1/4 mile section - within a mile is tested. The entire system is tested on - an annual basis.
Washington	- ASTM skid trailer is used to check high accident locations. - The entire system is rated every other year and a one mile - section is used. Data is part of a separate system.

becomes part of a separate data system used only to detect those pavement sections which fall below a specified trigger value, normally taken as 30.

Status of Indiana's PMS

The Indiana Department of Highways (IDOH) is currently in the process of developing a pavement management system for the Interstate, Federal-aid primary, and Federal-aid secondary system (see Figure 2.6).

In 1981, roughness measurements were performed on 98.4 percent of the testable miles for the Interstate system, on 93.5 percent of the Federal-aid primary system and 91.8 percent of the Federal-aid secondary system.

Friction testing was conducted on 97.4 percent of the Interstate mileage, 73.9 percent of the Federal-aid primary, and 46.2 percent of the Federal-aid secondary system.

Dynaflect measurements are made on selected projects, primarily on those pavement sections which showed a high roughness number and are badly deteriorated.

During 1982 the State developed rating forms for both flexible and rigid pavements. These forms were used to rate those pavement sections which have a roughness number greater than 1400 counts per mile for asphalt pavements and

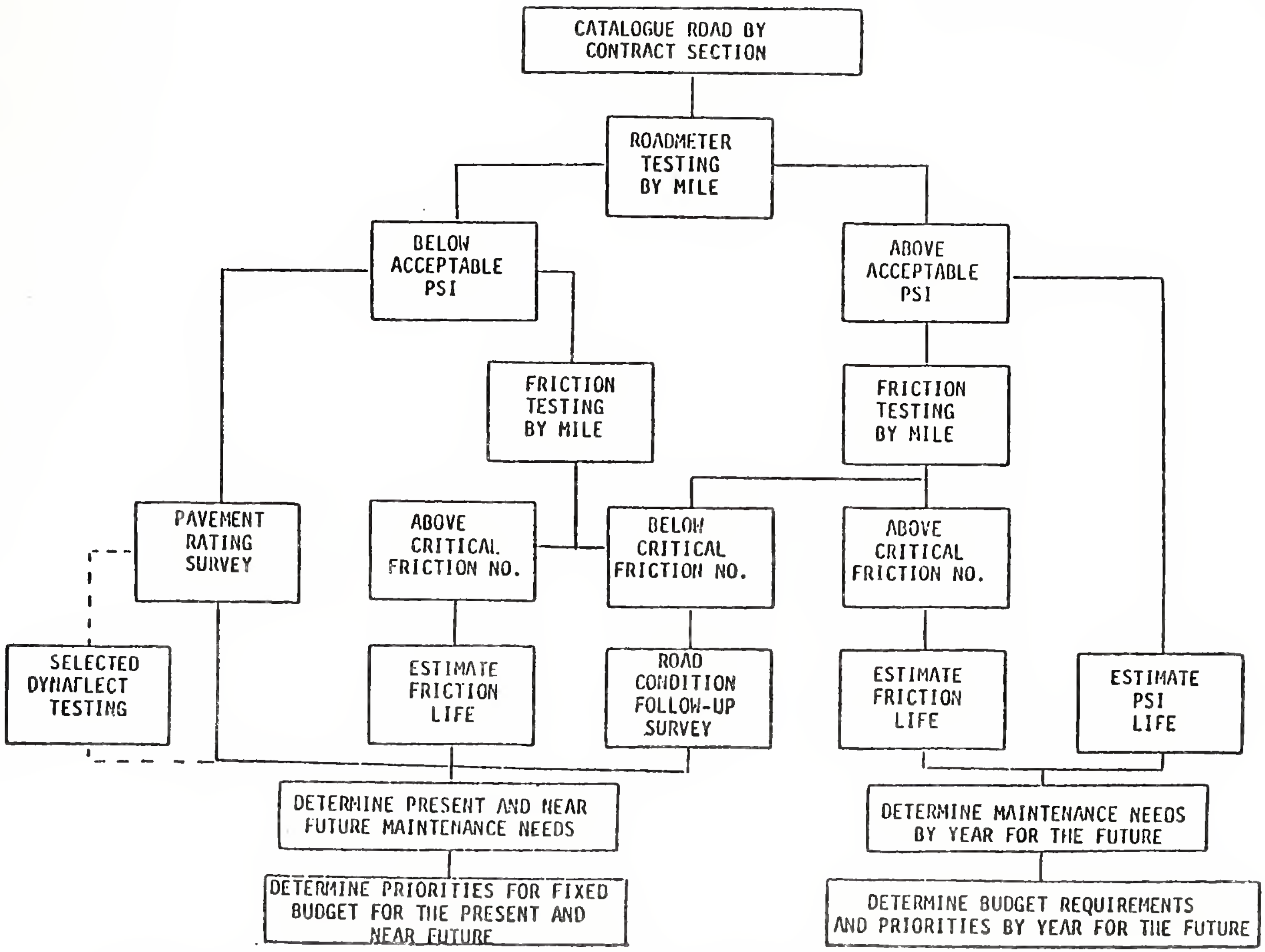


Figure 2.6 Testing Sequence in Indiana's Pavement Management System. [93]

2000 for concrete interstate pavements.

Predicting equations have been developed to estimate friction life and PSI life.

The pavement management efforts have the full support of top management. A pavement management task force was established during the fall of 1982 to address the State's immediate needs and to decide the course of action to be taken in order to implement successfully a pavement management system in Indiana.

In order for Indiana to be fully able to implement a pavement management program, it is necessary to develop appropriate optimization techniques to ensure that the most cost-effective funding and timing strategies are employed on each pavement section of the network.

An Overview of Optimization Techniques Used in PMS

Linear Programming

The Arizona Department of Transportation has developed an optimization model for their pavement management system. The model was formulated as a constrained Markov decision process converted to a linear programming framework [27,28,29]. The objective of the optimization model is to select the

least-cost maintenance policies while achieving minimum standards on road conditions.

Integer Linear Programming

Lu and Lytton developed a computer program using a zero-one integer linear programming technique for determining optimal maintenance strategies [36]. The model maximizes the overall effectiveness of maintenance activities subject to constraints such as limited resources and minimum requirements of pavement quality and service life. It uses the current pavement condition, potential gain of rating, and probability of survival as input.

Artman et al.[59] developed a network level computer program for the U.S. Air Force which uses a heuristic procedure for solving the zero-one integer linear programming model. The optimization model maximizes the pavement's performance weighted by the relative value of each project in the network. The heuristic procedure solved over 90 percent of the objective function when compared to the continuous linear programming solution.

Dynamic Programming

Zegeer et al.[96] developed a computer program which uses a dynamic programming procedure combined with an economic analysis to assist decision makers in optimizing

expenditures for Kentucky DOT's pavement resurfacing program. Procedures were developed to compute benefits and costs of proposed projects to determine which pavement sections should be rehabilitated under a given budget. The only cost input to the program was the resurfacing cost of each project.

Other Techniques Used in Pavement Management

Goal Programming

Goal programming is an optimization technique which is capable of handling decision problems with multiple goals [60,61]. This technique utilizes an ordinal hierarchy among conflicting multiple goals in order that the lower goals are considered only after the higher goals are satisfied [62]. Muthusubramanyan and Sinha [63,64] have applied this technique to the multi-objective decision problem of highway system maintenance and preservation.

Factorial Design

Fernando and Hudson [65,66] developed a method for formulating an index for establishing rehabilitation and maintenance priorities at the network level PMS. The rational factorial rating method is based on a half-replicate of a 2^6 which involves the following factors

(decision variables) each fixed at two levels:

1. Pavement type
2. Degree of Distress
3. Present Serviceability Index (PSI)
4. Traffic
5. Amount of rainfall
6. Amount of freeze-thaw

The priority index is essentially the dependent variable of a regression equation using the above factors as independent variables. The equation used to compute the priority index for the network level is shown below:

$$P.I. = 5.4 - 0.0263(RF) - 0.0132(FT) - 0.4LOG_{10}(ADT) + 0.749(PSI) + 1.66(DISTRESS) \quad (2.6)$$

R^2 = 97.8 % Std. Error Estimate = 0.31

where:

PI = priority index (0 to 10);

RF = amount of rainfall;

FT = amount of freeze-thaw;

ADT = average daily traffic;

PSI = present serviceability index;

DISTRESS = degree of pavement distress.

Summary

This chapter presented an overview of the pavement management programs currently used in the United States and abroad. A brief description of the elements of pavement management and its potential benefits are also discussed herein. A summary of the pavement management practices, primarily the types of data to be collected, equipment used, and frequency of measurement, are also discussed in this chapter. An overview of the optimization techniques used in existing PMS are also reviewed.

It is interesting to note that most of the highway agencies that have initiated pavement management programs at both the network and project level still do not have an optimization technique for allocation of rehabilitation funds. This research project is aimed toward the development of an optimization model which can be used by the Indiana Department of Highways as part of its pavement management program. The following chapter describes the methodology used in this study to develop the optimization model.

CHAPTER 3

IDENTIFICATION OF PERFORMANCE FACTORS AND DEVELOPMENT OF EQUIVALENT PERFORMANCE INDICES

Introduction

This chapter describes the performance factors considered and the reasoning involved behind the selection of them. The methodology used for developing the equivalent performance indices for each performance factor is also described in this chapter. The importance of the equivalent performance curves in the development of the optimization model is also discussed herein.

Description of Performance Indicators

Table 3.1 shows a list of factors that are deemed to be good indicators in predicting pavement deterioration. In the following paragraphs, the performance indicators considered in this project are briefly described.

Directional ADT

This is the average daily traffic in vehicles per day using the facility in one direction. The directional ADT information was obtained from the latest traffic flow maps

Table 3.1 List of Performance Factors Related to Pavement Deterioration.

Performance Factor	Is factor considered? Yes		No
Directional ADT	x		
Accumulated ADT	x		
EAL18000			x
Accumulated EAL18		x	
Increase in Total EAL18		x	
Remaining Life (in terms of EAL)			x
Roughness Number	x		
Increase in Roughness Number	x		
Pavement Age	x		
Pavement Distresses (PCI)	x		
Pavement Thickness			x
Surface and Pavement Type (JRC,CRC,AC)	x		
Friction Number	x		
Reduction in Skid Resistance	x		
Subgrade Type			x
Pavement Deflection			x
Drainage			x

and from the Traffic Statistics Report published by the Planning Division of Indiana Department of Highways [67,68].

Accumulated ADT

The accumulated ADT is the total number of vehicles that have used the facility since it was opened to traffic or since the last time a major rehabilitation was performed in the pavement section in question. It is essentially the total area under the ADT-Pavement Age curve. The following equation was used to compute the accumulated ADT [69]:

$$\text{Accumulated ADT} = \frac{ADT_o(365)}{\log_e(1+g)} \left[(1+g)^{age}-1\right] \qquad (3.1)$$

where:

ADT_o = ADT when opened to traffic = $\dfrac{ADT_p}{(1+g)^{age}}$;

g = annual traffic growth rate;

age = pavement age (1982 - year opened to traffic);

ADT_p = present ADT.

An annual traffic growth rate of 4 percent was used in this study. This growth rate is based upon previous studies conducted by JHRP for the Indiana Department of Highways and is also the estimate recommended by the AASHTO in its design procedure [71].

EAL_{18}

The EAL_{18} is a factor which relates the effect on pavement deterioration of any axle load to an equivalent 18 kip

single axle load [70,71]. This axle load was selected since it was the maximum legal load most used in the United States at the time of the AASHO Road Test. The AASHO equivalency factors F_j, as determined at the Road Test, have been generalized to relate any axle load on pavement distress to the distress caused by an 18-kip axle load.

To calculate the EAL_{18} per truck for any pavement section the following equation is normally used:

$$EAL_{18} = N_j \times F_j = \sum_{i=1}^{n} N_j \times \frac{W_j}{18000}^4 \qquad (3.2)$$

where:

EAL_{18} = number of equivalent 18 kip single axle; loads for pavement segment in question;

N_j = number of actual repetitions of axle load W_j ;

W_j = axle load in question in lbs;

n = number of load distribution intervals from which single axles were recorded.

The information required to compute the EAL_{18} can be obtained from the loadometer studies conducted in Indiana.

Accumulated EAL_{18}

The accumulated EAL_{18} is the total 18-kip equivalent-axle loads since the pavement section was opened to traffic.

It is essentially the total area under the EAL versus Time curve. The cumulative EAL_{18} for any pavement section can be computed using the following equation [69].

$$\text{Accumulated } EAL_{18} = \frac{EAL_o(365)}{\log_e(1+g)}[(1+g)^{age}-1] \qquad (3.3)$$

where:

EAL_o = initial daily equivalent 18-kip single axle loads on the day the road is opened to traffic;

$EAL_o = (\frac{ADT}{2})(T)(\frac{EAL_{18}}{truck})$;

ADT = average daily traffic in veh/day for both directions;

g = annual traffic growth rate;

T = percent of trucks;

age = pavement age (1982 - year opened to traffic).

Roughness Number

The roughness number is a measure of the amount of $\frac{1}{8}$ inch movements of a standard vehicle with respect to the rear axle [97,98]. The roughness number is measured with a PCA roadmeter. The unit of measurement used in this study is counts per mile.

The Indiana Department of Highways has been using 2000 counts per mile as the cut-off value for interstate concrete pavements and 1400 for interstate bituminous pavements. The roughness number has been correlated to the present serviceability index (PSI) developed at the AASHO Road Test [71].

Change in Roughness Number

The Change in Roughness Number is the difference between roughness number readings measured on any given contract section between any two years (i.e. RN_{81} - RN_{79}). The change in roughness is a very useful indicator of the rate of deterioration of any given pavement section. For example, if two pavement sections have exactly the same roughness number at the present time and both are in need of a major rehabilitation, and there is enough money to improve only one pavement section (assuming all other factors are exactly the same such as traffic, age, climate, contract length, etc.), the pavement section with the greater change in roughness number should be chosen for major rehabilitation.

Pavement Age

Pavement age is defined in this research study as the number of years since the last time a major rehabilitation was performed in any given section. This information is available from the road life records of IDOH as well as in the skid and roughness annual inventory reports compiled by the IDOH Research and Training Center.

Pavement Condition Index

The pavement condition index (PCI) is a number between 0 and 100 that indicates the structural integrity and surface operational condition of the pavement section [33].

The methods used in this study to compute the pavement condition index for the interstate and the state highway system were different. For the condition survey conducted on the Crawfordsville Highway District, the forms developed by the Construction Engineering Research Laboratory (CERL) to rate concrete and rigid pavements for PCI computations were used. This method is based on deduct values. For the condition survey conducted in the interstate system, the rating forms developed by IDOH were used. The details pertaining to both pavement condition surveys are explained in the following chapter.

Pavement Thickness

This is the total thickness of the pavement structure, including base and subbase. This information is generally available in the IDOH Planning Division.

Pavement Type

In Indiana most of the pavements are classified into four major design categories. These are:

1. Flexible pavements
2. Jointed Reinforced Concrete pavements
3. Continuously Reinforced Concrete pavements
4. Overlay pavements

Flexible pavements include all asphalt surfaces constructed on top of a non-stabilized base and subbase courses on top of the natural subgrade. Included in this category are full-depth asphalt pavements.

Jointed Reinforced Concrete pavements (JRCP) are concrete pavements without an overlay, with joints typically spaced at 40 feet intervals.

Continuously Reinforced Concrete pavements (CRCP) are pavements without joints except construction joints and expansion joints at bridges and containing continuous reinforcing steel.

Overlay pavements are concrete pavements with an asphalt layer on top.

Friction Number

The friction number is a measure of the coefficient of wet sliding (skidding) friction at 40 mph between a wet pavement surface and a standard tire as described in ASTM E-274 and E-501 [74]. In Indiana the friction tests are

performed approximately one per mile for each contract section tested. The average of all tests within a contract section is normally used for evaluation purposes. It is common practice in Indiana to identify all pavement sections with an average friction number less than 30 irrespective of the type of pavement surface.

Selection of Performance Indicators

The six performance indicators finally evaluated in this research study are listed below:

1. Current Directional ADT
2. Accumulated ADT
3. Present roughness number
4. Change in roughness number between years
5. Pavement Condition Index (PCI)
6. Pavement Age

Pavement thickness was eliminated since it was assumed that pavements in service were designed for the loads which are actually imposed on them. In addition, it was felt that the relative weight assigned to this factor might not make a significant difference in the overall ranking of the contract section being considered. The South Dakota DOT includes pavement thickness as one of the factors in priority setting procedure. However, the relative weight assigned to it is actually less than 5 percent of the total weight

assigned to the performance elements considered by the state [92].

The Equivalent Axle Load and Accumulated EAL were eliminated for several reasons. First, at the present time Indiana does not collect truck weight distribution data on the Federal-aid secondary system. Even though an approximate estimate can be made based on data from weigh stations opened in the past, which is in the range of .30 to .40 EAL per truck, it was felt this number might just be a constant factor applied to every Federal-aid secondary road considered in the model, and thus would not change the final results of the optimization model.

The percent trucks is also considered a good indicator. However, this information was available from only 28 permanent stations as reported in IDOH Traffic Statistics report, 1981 [68].

For the reasons discussed above and at the suggestion of the IDOH, the present study included the current ADT as well as the accumulated ADT of each pavement section rather than EAL and accumulated EAL. The information on ADT was available for every pavement contract section considered herein.

The effect of climate was not considered since it was assumed that pavements were designed for the environmental effects of the geographical region in question. The problems associated with severe climatic conditions are indirectly taken into account in the pavement condition index which is one of the factors considered in this study.

Friction and change in friction number were eliminated for several reasons. First, based on the literature review, some of the states which have implemented pavement management programs, such as Florida and California [6,8,29,38], felt that friction plays a role only in those cases where the friction number is below a pre-determined value, say less than 30. In fact, it is required that every pavement section should have a surface with anti-skid properties. Therefore, if during any fiscal year there is pavement section with a friction number less than 30, irrespective of how rough is the pavement section or the magnitude of the distresses encountered, an immediate action is mandated. This is the main reason for the Indiana Department of Highways to require that in the optimization process friction data should be treated explicitly. The South Dakota DOT takes friction into account in priority setting procedure, however, the weight assigned to this factor is only 3 percent [92].

Pavement deflection was not considered in this study. The IDOH does not collect deflection data on a routine basis. Nor is there any future IDOH plan to collect state-wide pavement deflection measurements. In fact, at present only one of the states (Utah) that have developed pavement management systems at the network level, actually collects deflection data on a routine basis [75].

Drainage was not considered in this study, since the IDOH does not collect detailed drainage data on a routine basis for the entire highway network.

At this stage, the question can be raised as to how state highway agencies can analyze and evaluate the performance factors in the most efficient and cost-effective manner so that the information can be useful in pavement rehabilitation decision making process. Ideally, this can be accomplished if, in fact, the state can predict, from the roadway inventory and from the above factors, which pavement sections need immediate repair action as compared to those pavement sections which can still provide an acceptable performance in the years to come.

Decision to Use Pavement Contract Section

After the performance factors were chosen, it was necessary to decide what unit of measurement best represents

the current condition of any highway segment. The state of Arizona, for example, divides the highway network into 7,400 one-mile segments [27]. The normal practice, however, is to use the paving contract section as the smallest unit of measurement. In Indiana, the pavement contract section is used as the unit of measurement since pavement characteristics such as pavement thickness, age, width, drainage, materials, construction method, etc. are, in most cases, homogeneous throughout the entire section. Previous research projects conducted at Purdue University have shown that the paving contract section is the best experimental unit to be used in a comprehensive pavement evaluation system [76,77].

Decision to Use Milepost Number

One of the major items necessary for successful implementation of any pavement management program is the ability to associate all performance data to a common reference point. The milepost number seems to be a very good indicator for analyzing all the performance factors previously described.

For example, every characteristic of interest to the state can be projected visually on a two-dimensional graph where the performance factor associated with each highway

contract section is plotted in the vertical axis and the corresponding milepost number in the horizontal axis. Figures 3.1 and 3.2 show graphs of Roughness Number and Increase in Roughness Number against milepost number for Interstate 64 east during 1981. The type of pavement is also included in the graph. Each pavement contract section is represented by a horizontal segment enclosed within each consecutive pair of observations. Based on Figure 3.1 it can be noted that the only significant rough spot in interstate 64 east is a concrete pavement section located about 125 miles east of the Illinois-Indiana State Line. This contract section is about 0.4 miles long and the roughness number is close to 3000 counts per mile. With the exception of this pavement section, the roughness numbers along this route are quite uniform ranging between 500 and 1500 counts per mile throughout the entire segment.

In Figure 3.2 it can be noted that the increase in roughness number in Interstate 64 East is, in most cases, between 0 and 300 counts per mile. It is interesting to note that the pavement section which had a very high roughness number on Figure 3.1 is also deteriorating at a very high rate since the increase in roughness number experienced between 1979 and 1981 is in the range of 400 counts per mile which is at least 150 counts higher than the average

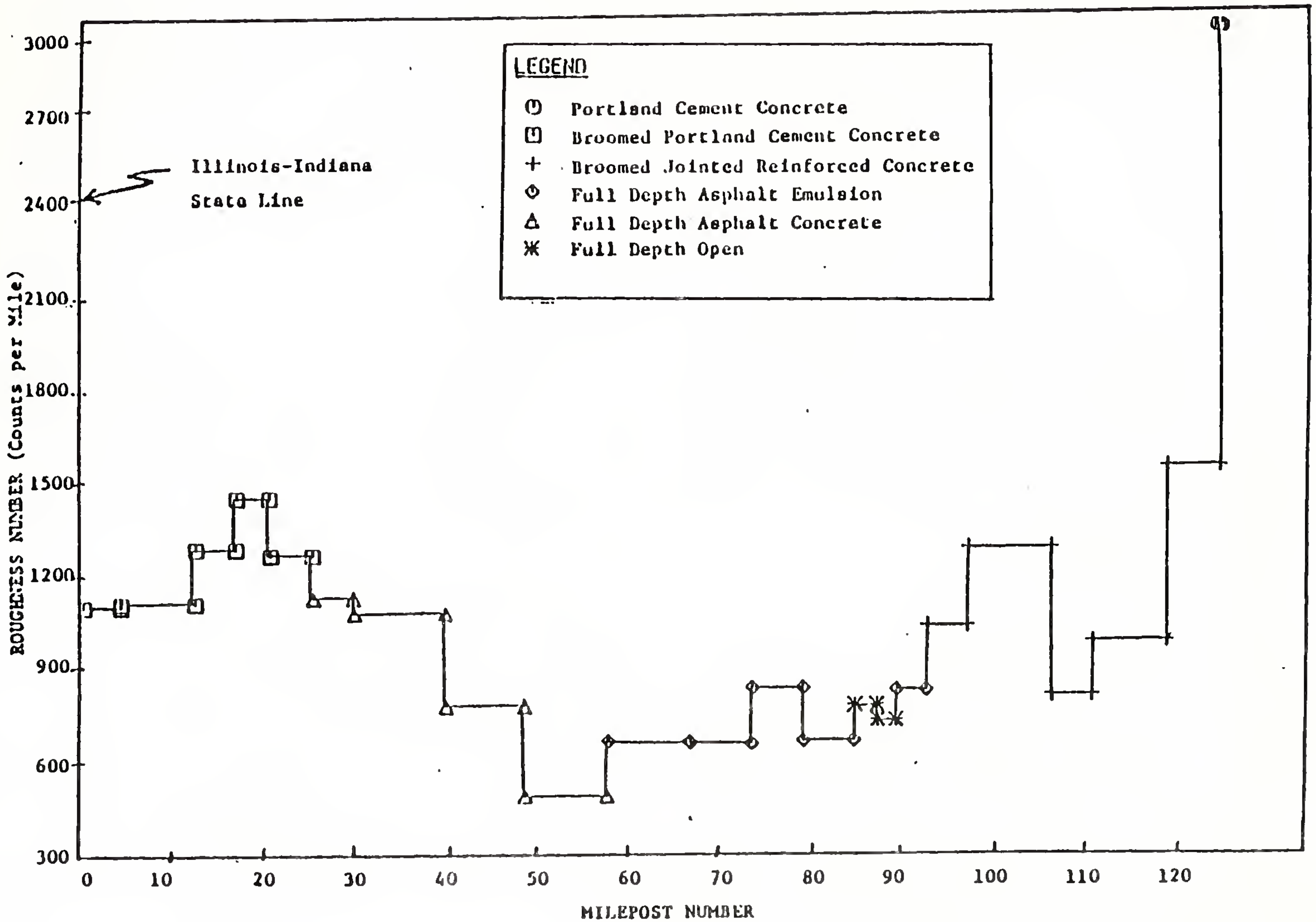


Figure 3.1 Roughness Number vs. Milepost Number for I-64 East (Indiana) During 1981.

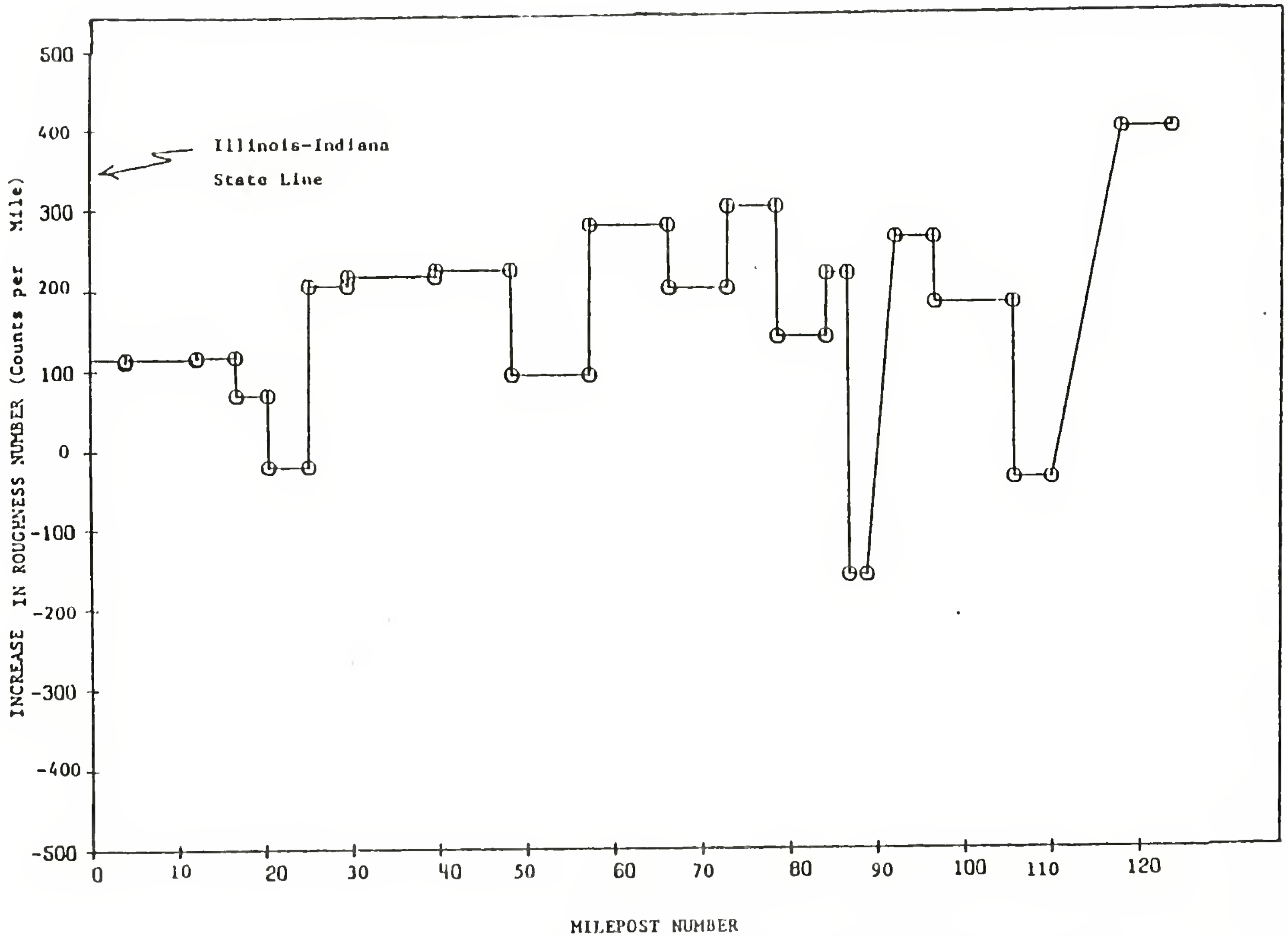


Figure 3.2 Increase in Roughness Number (1981-1979) vs. Milepost Number for I-64 East (Indiana).

increase in roughness experienced by the remaining 120 miles along this route.

It should be realized that these graphs can only be used during the initial stages of any pavement management process to identify those highway contract sections (or miles) which are consistently above or below a pre-determined trigger value associated with each performance factor being considered. To determine the proportion of miles (or contract sections) that can be rehabilitated during a given period of time, an optimization model must be formulated which best suits the needs of the highway agency in question.

It can be argued that a complete pavement management program should encompass both the graphical method during the initial stages to identify the deficient sections, and the optimization model to improve cost-effectively the overall condition of the pavement network.

Analysis of Performance Indicators

Once the performance indicators were selected and the pavement contract section was adopted as the unit of measurement, it was decided to determine the distribution of each of the factors in order to analyze explicitly the current condition of the pavement network. To accomplish

this task, plots were generated for each interstate route and for each performance indicator using the pavement contract section as the unit of measurement and the milepost number as the common reference point. Figures 3.1 and 3.2 are representative of the graphs which were generated for each interstate route for this purpose. Histograms were then constructed for each performance factor in order to establish trigger values for each factor being considered. The Statistical Package for Social Sciences (SPSS) [78] was used to generate histograms and frequency distributions for each of the performance factors considered in this study as well as for each road in the pavement network. A sample printout of roughness and friction number for Interstate 64 east during 1981 is shown in Figures 3.3 and 3.4. Cumulative frequency distributions were also developed for each performance factor to use the percentile value as an index which adequately represents the proportion of contracts exceeding a given percentile value. The 1981 data base was used as a starting point for this analysis.

Determination of Equivalent Performance Index Curves

In the previous section, the contract section frequency distributions of those factors which were considered relevant in predicting pavement performance, such as roughness, current ADT, pavement condition index, etc. were

Roughness Number Interval	CODE	ABSOLUTE FREQ	RELATIVE FREQ (PCT)	ADJUSTED FREQ (PCT)	CUM FREQ (PCT)
1-600	1.	1	4.5	4.5	4.5
601-1000	2.	10	45.5	45.5	50.0
1001-1400	3.	8	36.4	36.4	86.4
1401-1800	4.	2	9.1	9.1	95.5
1801-3000	5.	1	4.5	4.5	100.0
	TOTAL	22	100.0	100.0	

```
             CODE
                  I
1-600        1.   ****** (      1)
                  I
                  I
601-1000     2.   ************************************************************ (      10)
                  I
                  I
1001-1400    3.   ************************************************ (      8)
                  I
                  I
1401-1800    4.   ************ (      2)
                  I
                  I
1801-3000    5.   ****** (      1)
                  I
                  I
                  I.........I.........I.........I.........I.........I
                  0         2         4         6         8         10
         CONTRACT FREQUENCY

                  VALID CASES      22        MISSING CASES      0
```

Number of contract sections analyzed: 22

Figure 3.3 Computer Printout Showing Distribution of Roughness Number by Contract Section During 1981 in I-64 East (Indiana).

Friction Number Interval	CODE	ABSOLUTE FREQ	RELATIVE FREQ (PCT)	ADJUSTED FREQ (PCT)	CUM FREQ (PCT)
50.1-Highest	1.	7	31.8	33.3	33.3
40.1-50.0	2.	12	54.5	57.1	90.5
35.1-40.0	3.	1	4.5	4.8	95.2
1.0-30.0	5.	1	4.5	4.8	100.0
Missing Values	0	1	4.5	MISSING	
	TOTAL	22	100.0	100.0	

```
                 CODE
                      I
50.1-Highest      1.  ****************** (      7)
                      I
                      I
40.1-50.0         2.  ****************************** (      12)
                      I
                      I
35.1-40.0         3.  *** (      1)
                      I
                      I
 1.0-30.0         5.  *** (      1)
                      I
                      I
                  0   *** (      1)
           (MISSING)  I
                      I
                      I.........I.........I.........I.........I.........I
                      0         4         8         12        16        20
         CONTRACT     FREQUENCY

     VALID CASES       21        MISSING CASES      1
```

Number of contract sections analyzed: 22

Figure 3.4 Computer Printout Showing Distribution of Friction Number by Contract Section During 1981 in I-64 East (Indiana).

analyzed individually for each interstate route. Simply stated, the afore-mentioned procedure was very useful in answering questions such as: How many miles of a particular interstate route within a particular District have roughness number or any other performance factor in excess of a given amount during the current fiscal year? On the other hand, the plots which were generated for every route using the milepost number as the common denominator, were useful in detecting the exact location of the high and low points within the stretch of road under consideration for only that factor. If the decision-maker is only interested in the main effects of one factor, then the above procedures are sufficient to detect those miles which are above or below a pre-determined trigger value. On the other hand, if the interest is to determine the combined contribution of several factors, the above procedure is not sufficient. It is a fact that pavement deterioration is a combination of many factors. Furthermore, some factors are more critical than others. It is therefore necessary to develop a method that can take into account the effects of several factors, and at the same time can incorporate the relative weight or importance of each performance factor in question.

At the present time, the performance factors considered in this study have different units of measurement. For example, roughness number is measured in counts per mile, ADT is

measured in vehicles per day, pavement age is taken as the number of years since the last major improvement, and so on. In addition, each performance factor has a different trigger value associated with it and the value itself is a function of the type of pavement being considered (i.e. jointed reinforced concrete pavement, conventional asphalt pavement, etc.) Therefore, it is necessary to develop an equivalent unit of measurement which can be effectively used to compare all performance factors at the same level.

To accomplish this task, the concept of the equivalent performance index was developed. The equivalent performance index (EPI) is an index from 0 to 100 used to represent the effect of each of the performance factors considered in the study. The value of 0 represents a very poor performance for the factor in question, while 100 represents an excellent performance. The development of the EPI is based primarily upon the cumulative distribution of each of the performance factors being considered. Equivalent Performance Curves were prepared for both the interstate system as well as the secondary system. The curves for the secondary system were developed primarily from pavement sections located within the Crawfordsville Highway District since the pavement condition survey which was conducted as part of this

research project was also conducted on this district. All the curves were developed using the roughness inventory file corresponding to 1981 and 1979 since it was the most reliable data available at the time of this study.

Interstate System

Figure 3.5 shows the equivalent performance curves developed for the interstate system for roughness number. The curves were developed from the roughness inventory data corresponding to 1981. A total of 226 pavement contract sections was considered to develop the equivalent performance curve for concrete pavements as compared to 74 contracts for asphalt (overlay) pavements. Continuously reinforced concrete pavements were treated separately. It can be seen in Figure 3.5 that the performance curve for asphalt pavements is more uniform (steep) as compared to concrete performance curve (smooth S curve). In addition, the concrete performance curve is shifted much more to the right as compared to the asphalt performance curve. This implies that concrete pavements in the state are more rough than asphalt (overlay) pavements. Because of this variation, different trigger values are used by the IDOH to identify deficient asphalt and concrete pavements. It is interesting to note that the EPI developed in this study is related to the proportion of roads below a given value. At the present

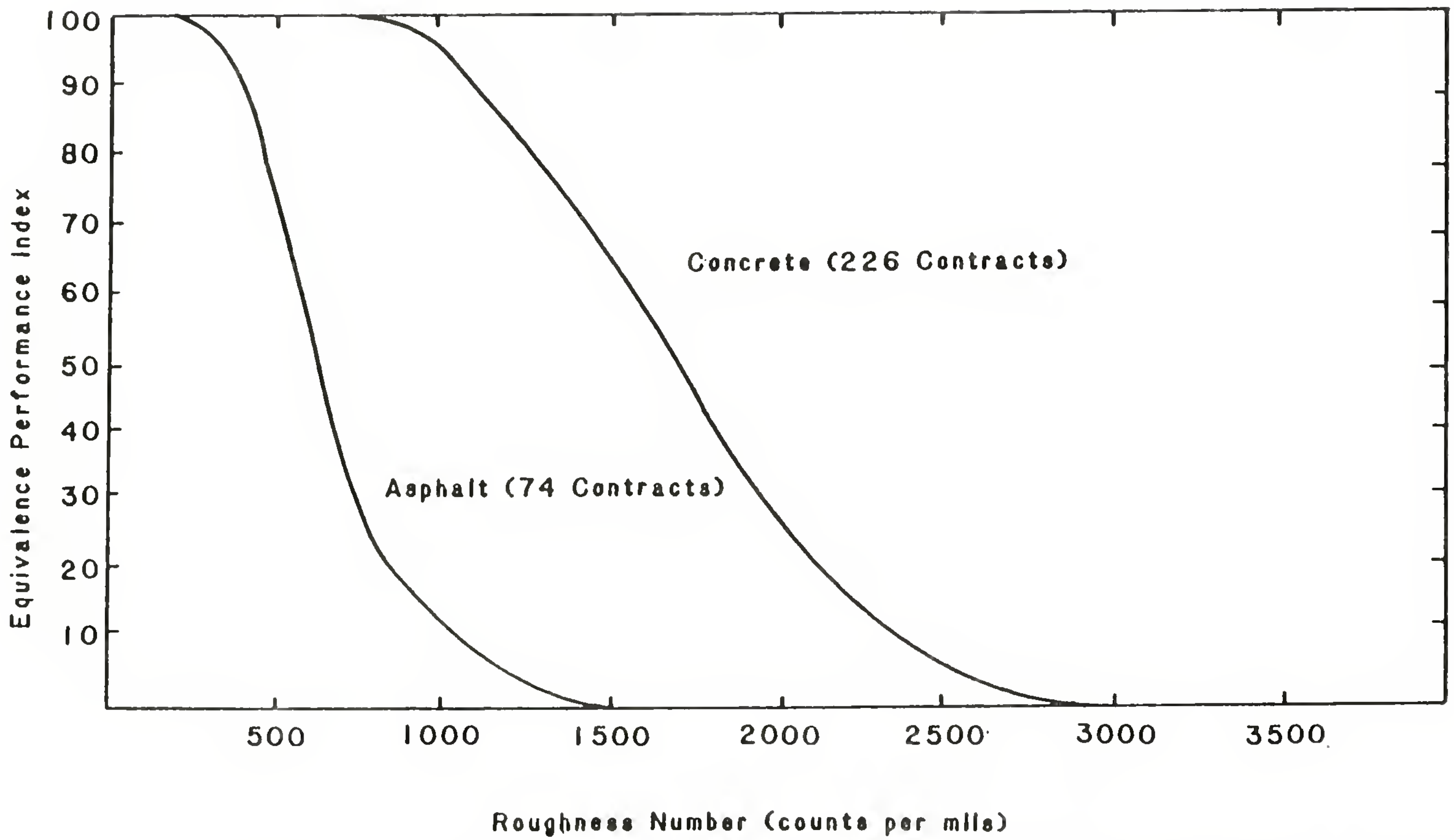


Figure 3.5 Roughness Number Equivalence Performance Index (EPI) for the Interstate System.

time the IDOH uses 2000 as the cut-off point for concrete pavements and 1400 for flexible pavements. This corresponds approximately to an EPI of 25 and 5 for concrete and flexible pavements, respectively.

Figure 3.6 shows the equivalent performance curves for change in roughness number for the interstate system for both asphalt (overlay) and concrete pavements. The change in roughness number was calculated using the roughness data from years 1979 and 1981. The change in roughness number represents the rate of deterioration of the pavements in the network. If all other performance factors are the same and the roughness number in fiscal year in question is the same for two pavement sections being considered, the section which has the higher change in roughness number should be considered first if there is enough money to improve only one of the sections. A total of 216 contract sections was considered for concrete pavements and 52 sections for asphalt pavements.

Figure 3.7 shows the equivalent performance curve for roughness number for CRC pavements in the intestate system during 1981. This curve was developed using data from 44 pavement contract sections on which roughness information was available. It can be seen in Figure 3.7 that an EPI less than 15 corresponds to a CRC pavement exceeding a

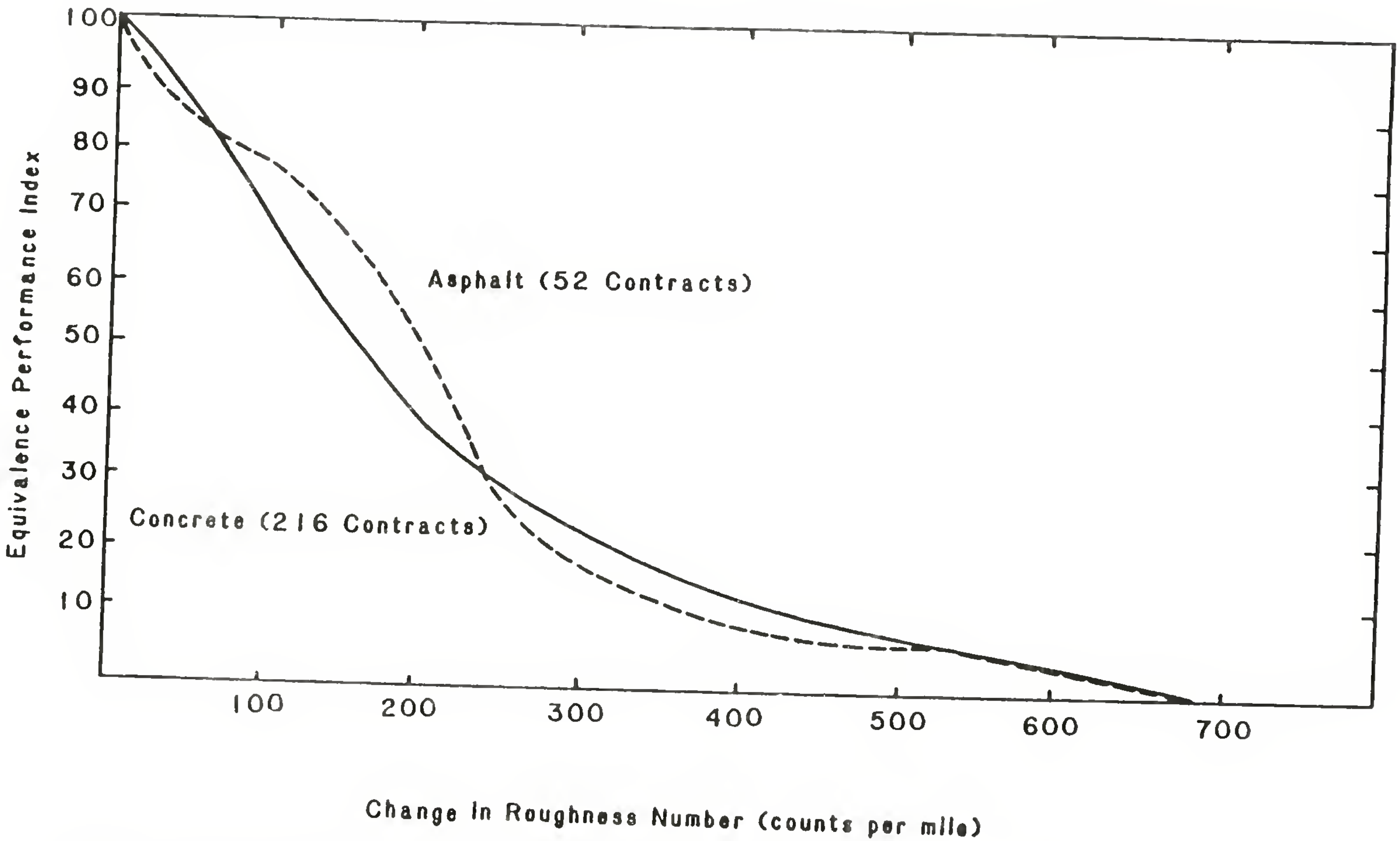


Figure 3.6 Equivalence Performance Index (EPI) for Change In Roughness Number for the Interstate System.

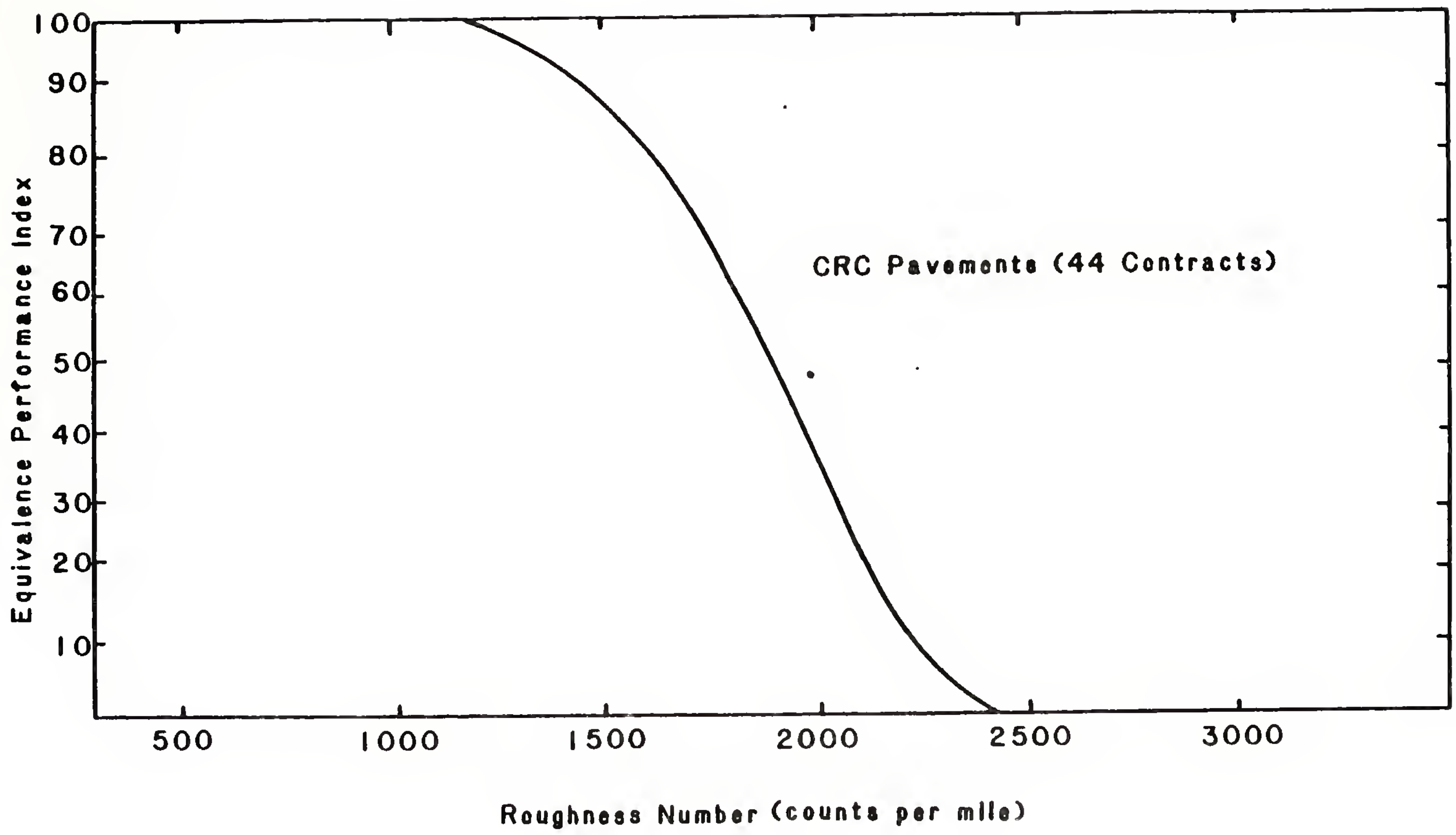


Figure 3.7 Equivalence Performance Curve for Roughness Number in CRC Pavements.

roughness number of 2000. Therefore during fiscal year 1981, 15 percent of the CRC contract sections exceeded a roughness number of 2000.

Figure 3.8 shows the equivalent performance curve for change in roughness number for CRC pavements in Indiana developed from roughness inventory files of 1979 and 1981. Thirty-nine of the forty-four contract sections used to plot Figure 3.8 were considered in this graph. Based on this figure an EPI of 20 represents all those contract sections exceeding a change of roughness of 200 counts per mile.

Secondary System

Figure 3.9 shows the roughness number equivalent performance curves for asphalt and concrete pavements for the Crawfordsville Highway District. The curves were developed using the roughness information of 239 asphalt pavement contract sections and 33 concrete pavement contract sections. It is interesting to note that asphalt pavements in the state system have a higher roughness number than concrete pavements as compared to the interstate system in which the concrete pavement sections experience a higher roughness number than asphalt pavement sections. In state routes, an EPI of 20 for concrete pavements corresponds to a roughness number exceeding 1750 counts per mile for concrete pavement

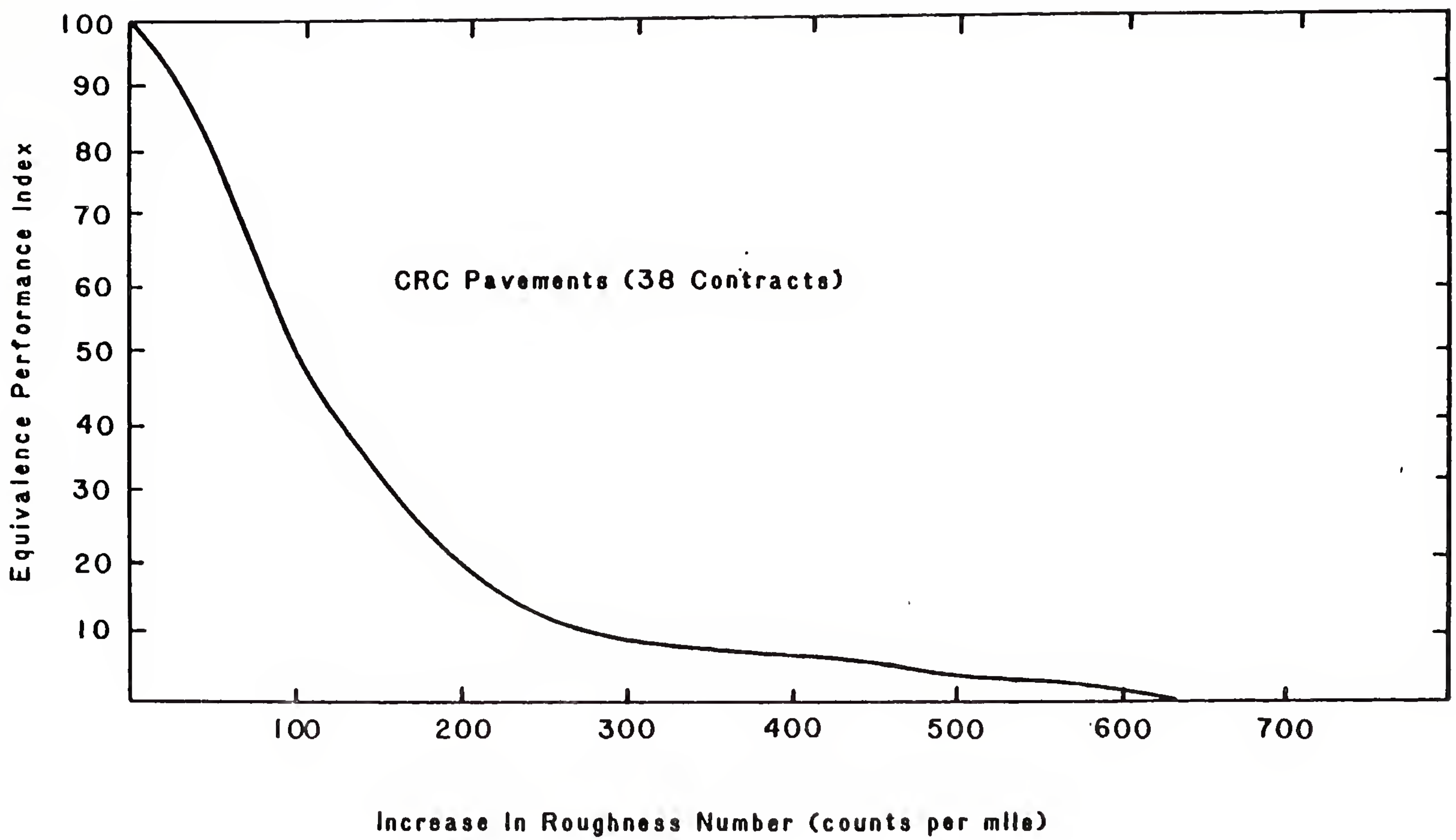


Figure 3.8 Equivalence Performance Curve for Increase In Roughness Number (CRC Pavements).

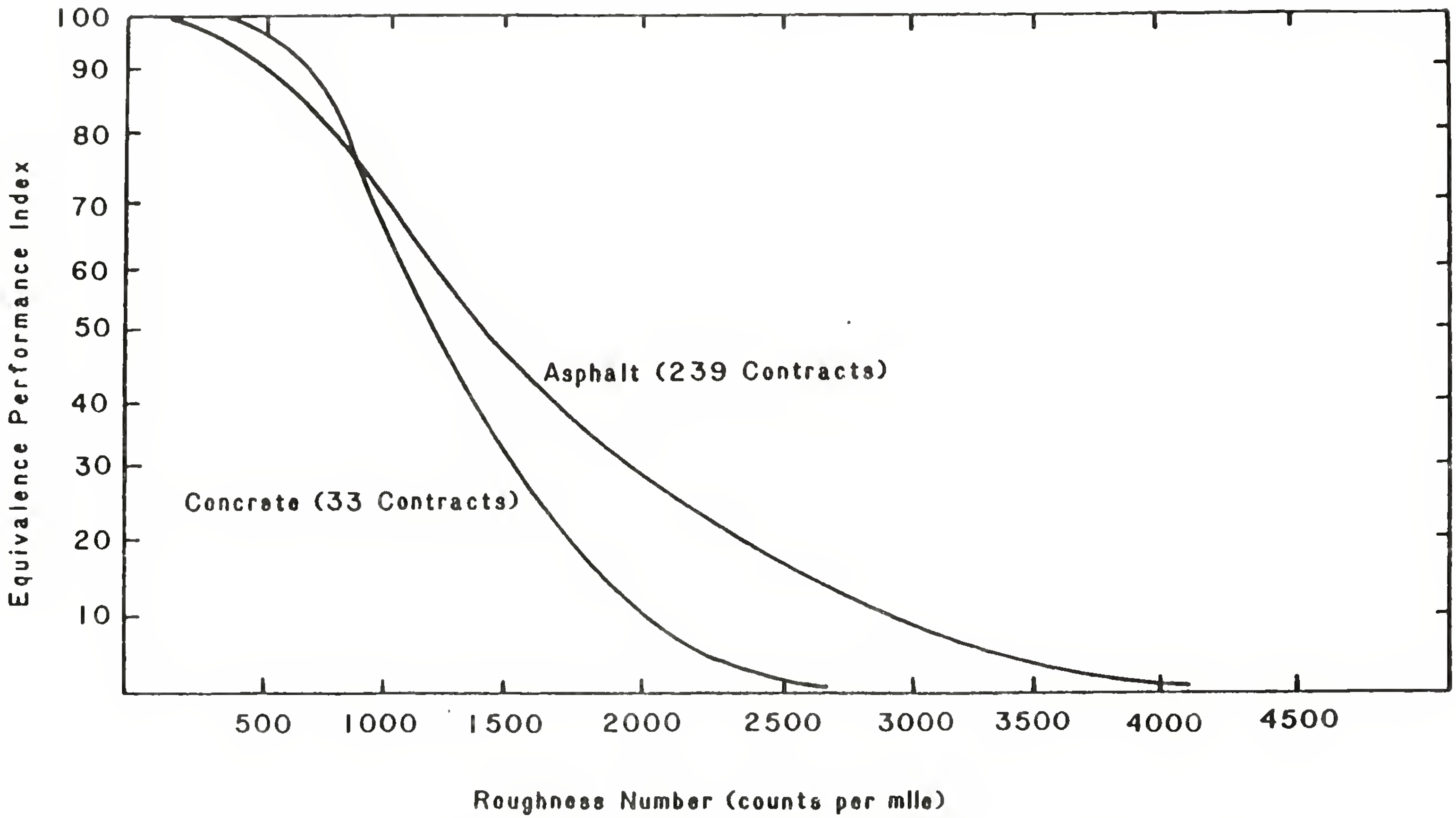


Figure 3.9 RoughnessNumber Equivalent Performance Index (EPI) For State Routes.

sections and 2700 counts for flexible pavement sections.

Importance of Weighing Performance Factors

If each EPI curve is analyzed individually, it can be helpful in establishing priorities as to which pavement sections are in need of maintenance (if EPI is below a predetermined value), what type of failure is present, and also to what extent the problem has progressed. However, in order to obtain an indication of the overall condition of the stretch of road in question and to gain insight as to the most efficient form of rehabilitation to pursue, the factors must be analyzed collectively as well as individually. The interaction between these factors plays a major role in determining the type of maintenance strategy required. In other words, if a pavement section is not rehabilitated within a certain period of time, a present pavement distress may lead the pavement section to deteriorate to a higher level that a major reconstruction would be necessary.

Description of the Graphic Interactive Method

The graphic interactive method is a graphical technique which is used to evaluate the combined effect of performance factors which are of primary interest to decision makers. The term "interactive" comes from the fact that one actually

analyses four graphs at the same time in order to check the interaction of the performance factors being considered. The combined effect of the factors can then be analyzed by inspection. In this study, the interest is to identify those pavement sections which fall below the specified trigger values associated with the performance factors being investigated.

In reality, the technique used in this study is a combination of the graphical method and a weighted technique, since weights are required to consider the importance of each performance factor being investigated.

The outcome of the graphical technique is the number and exact location of miles (contract sections) which fall consistently below the trigger values specified by the decision makers(in terms of EPI) at the start of the analysis period. In other words, this method is useful in detecting those pavement sections which are in "poor" condition and are normally classified as "bad" sections. These are the contract sections that are used as input to the optimization program.

In order to use the graphical interactive technique for this research project the following steps were necessary:

1. Identify the performance factors which are of significant interest to the highway agency.

2. Transform the performance factors to an equivalent performance scale.

3. Establish a common reference point

4. Establish a common unit of measure

5. Establish the weights of each performance factor

The performance indicators considered in this study were described in previous section. It included roughness, ADT, pavement condition index, cumulative ADT, and pavement age. The equivalent performance scale adopted herein was based on the cumulative frequency distributions discussed in the previous sections and developed for different types of pavements and highway classes. The common reference point used is the milepost number. The common unit of measurement is the pavement contract section. The weights assigned to each performance factor and the actual application of the graphical interactive technique are described in detail in Chapter 7.

The following chapter describes the pavement condition surveys which were conducted as part of this research study on both the interstate system and Federal-aid primary and secondary systems.

CHAPTER 4

PAVEMENT CONDITION SURVEYS

Introduction

The purpose of this chapter is to describe the details pertaining to the two pavement condition surveys conducted in Indiana as part of this research project. The criteria used in the selection of pavement sections is described herein as well as the sampling procedures employed. The rating forms used in the condition surveys to rate both concrete and flexible pavements are also described. The current pavement condition is used as input to the mathematical model developed in this research.

Purpose of Condition Surveys

The primary purpose for conducting a pavement condition survey is to obtain an objective measure of the different types of pavement distresses currently encountered on Indiana's interstate system as well as on the Federal-aid primary and secondary systems. Most of the states which have implemented pavement management systems at the network level conduct some sort of surface condition survey. The condition surveys take into account not only the type of

distress, but also the magnitude and severity of it. Most of the states have also developed rating manuals to suit the particular needs of their pavement network [6,33,44,45,46,49,57,79,80,81,82]. Some states use standard rating manuals published by the Federal Highway Administration [83].

Description of Condition Surveys

As part of this study, two pavement condition surveys were conducted. The first condition survey, performed in the Interstate system during the summer of 1982, was conducted by the Indiana Department of Highways (IDOH). The second condition survey, performed during the fall of 1982 on pavement sections located in the Crawfordsville Highway District, was conducted by the Joint Highway Research Project (JHRP) staff. The two condition surveys were independent. The Interstate survey forms were designed by the IDOH staff specifically for the Interstate network. The survey to rate pavements in the Federal-aid primary and secondary systems, adopted an existing rating procedure which has proven in the past to give meaningful results [33].

In the following sections the procedures used by the two condition surveys are described.

Interstate Condition Survey

The rating forms developed by IDOH for the interstate condition survey to rate flexible and rigid pavements are shown in Figures 4.1 and 4.2. The survey was performed on only those concrete pavement sections with a roughness number greater than 2000 and on asphalt pavements with a roughness number greater than 1400 counts per mile. These trigger values were established by a previous research project sponsored by the Joint Highway Research Project on pavement evaluation [76,77]. For each mile of a contract pavement section exceeding the above trigger values, a 200 foot long section was chosen at random as a sample section using a table of random numbers. For example, if a particular contract section was 5 miles long, 5 ratings were performed on this contract section.

If the contract section contained dual lanes, the 200 foot section was chosen in the travel lane. If the contract section had three-lanes, such as I-465, the 200 foot section was chosen in the middle lane. Overlayed pavements were considered as flexible pavements and were rated using the Flexible Pavement Rating Form.

FLEXIBLE PAVEMENT RATING FORM

GENERAL COMMENTS

— One rating form is required for each mile of the contract. If the contract is less than one mile only one form is required.

— For each mile a 200 foot long section is chosen, at random, on which the rating is performed. The random section is obtained by the procedure outlined within the table of random numbers. If the contract is dual lane the 200 foot section should be chosen in the travel lane. If the contract is three lane, such as I 465, the 200 foot section should be chosen in the middle lane.

— The seperate rating forms should be assimilated and return to the Research and Training Center within 30 days of receivel. Distribution will be made by the Research and Training Center.

— Asphalt overlayed concrete is considered as flexible pavement and is rated on the Flexible Pavement Rating Form.

GENERAL INFORMATION REQUIRED

District ____________ Contract Length ____________ Street or Route No ____________

Contract No ____________ City or County ____________ Pavement Width ____________

Surface Type ____________ Roughness No ____________ Friction No ____________

Is the Pavement an Overlay or Full Depth? ____________ ADT ____________ % Trucks ____________

SPECIFIC INFORMATION REQUIRED

General Location of 200 feet Section within Contract* ____________

____

Rating Performed By ____________ Title ____________

*Reference to direction and landmark or distance to contract

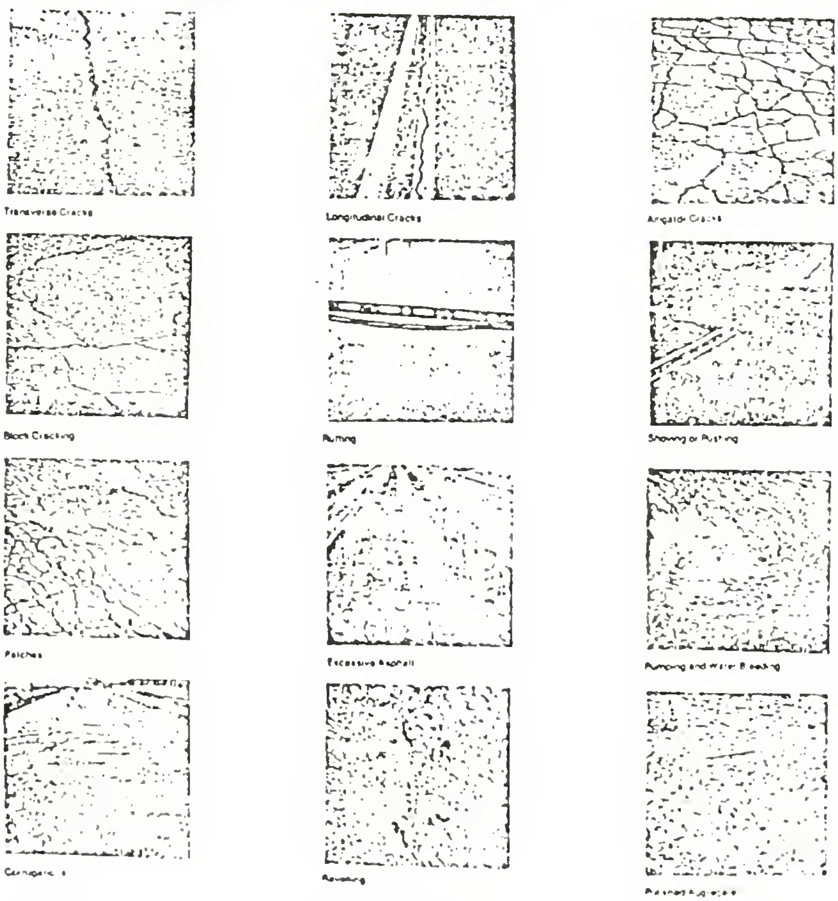


Figure 4.1 Flexible Pavement Rating Form Used in Interstate Condition Survey.

DEFECT	RATING SCALE	RATING CRITERIA BY PAVEMENT TYPE	RATING	DEFECT DESCRIPTION
Transverse Cracks	0-5	0-4 hairline cracks = 0-1 (rating) 5-10 hairline cracks = 2-3 (rating) more than 10 hairline cracks = 4-5 (rating)	———	Cracks approximately at right angles to centerline. Rate the extent and severity of cracking. Extent is rated relative to number of cracks in 200 foot section. Severity is rated from hairline cracks (less than 1/8 inch) to severe cracks (greater than ¼ inch). Sealed cracks are rated as hairline unless reopened. Severe cracks should be rated higher than hairline cracks. Cracks less than 18 inches in length are not considered.
Longitudinal	0-5	0-50 feet of hairline cracking = 0-1 (rating) 51-100 feet of hairline cracking = 4-5 (rating)	———	Cracks approximately parallel to the pavement centerline. Rate the extent and severity of cracking. Extent is rated relative to total length of cracks in 200 foot section. Individual cracks are added to obtain estimated total length of cracking. Severity is rated as the average width of crack from hairline (less than 1/8 inch) to severe (greater than ¼ inch). Sealed cracks rated as hairline unless opened. Severe cracks should be rated higher than hairline cracks. Cracks less than 18 inches in length are not considered.
Alligator Cracks	0-10	5% = 5 (rating) thru 100% = 10 (rating)	———	Interconnecting cracks forming the typical patterns resembling an alligator's hide. Sealed cracks are rated the same as open cracks. Extent is rated relative to percentage of pavement surface area in 200 foot section denoting alligator cracking. Severity is rated from the initial appearance of fatigue cracks in the wheel paths to other pattern-type fatigue cracks generally outside the wheel paths. A higher rating should be assigned to severe alligator cracking.
Block Cracking	0-5	0% = 0 (rating) thru 100% = 10 (rating)	———	Interconnecting cracks forming series of large polygons usually having sharp angles at corners. Rate extent and severity of cracking. Extent is rated relative to percentage of pavement surface area in 200 foot section cracked. Severity is rated from initial cracking (less than 1/8 inch) to severe cracking (greater than ¼ inch). A higher rating should be assigned to severe block cracking.
Rutting	0-10	Average rutting 1/8"-1/4" = 0-2 (rating) Average rutting 1/4"-1/2" = 3-5 (rating) Average rutting over 1/2" = 6-10 (rating)	———	A rut is a longitudinal surface depression in the wheelpaths at least 20 feet long. Rate the severity of depth of rutting in 200 foot section as outlined under Rating Criteria. To obtain average rutting at least 10 readings should be taken throughout the rutting area and averaged. Ruts less than ⅛ inch in depth are not rated.
Shoving or Pushing	0-10	0% = 0 (rating) thru 100% = 10 (rating)	———	Shoving or pushing of pavement lays due to insufficient bond and stability. Typically found at intersections resulting from vehicle braking action. Extent of shoving or pushing is rated relative to the percentage of surface area in 200 foot section denoting defect. No degrees of severity are defined.
Patches	0-10	0% = 0 (rating) thru 100% = 10 (rating)	———	Patches are temporary or permanent corrections to damaged pavements. Rate extent and severity of patching. Rate extent relative to the percentage of pavement surface area in 200 foot section which is patched. Rate severity relative to the condition of the patches from good condition performing satisfactorily to poor condition, ride quality is significantly affected. A higher rating should be assigned to poor condition patches.
Excessive Asphalt	0-10	0% = 0 (rating) thru 100% = 10 (rating)	———	Excessive (bleeding) asphalt is film of bituminous material on the pavement surface which creates a shiny, glass-like, reflecting surface that usually becomes quite sticky. Extent of bleeding is rated relative to percentage of pavement surface area in 200 foot section denoting defect. No degrees of severity are defined.
Pumping and Water Bleeding	0-10	If no pumping observed rate as 0. If any amount of pumping is observed rate as a 10	———	Pumping is the ejection of water and fine materials under pressure through cracks under moving loads. Water bleeding occurs where water seeps slowly out of cracks in the pavement surfaces. If pumping or water bleeding exists anywhere in the sample unit it is counted as occurring.
Corrugations	0-5	0% = 0 (rating) thru 100% = 10 (rating)	———	Corrugation is a form of plastic movement typified by ripples across the asphalt pavement surface. Rate the extent and severity of corrugations. Extent is rated relative to percentage of pavement surface area in 200 foot section denoting corrugations. Severity is rated from light corrugations causing some vibration of the vehicle but creates no discomfort, to severe corrugations causing excessive vibration of the vehicle which creates substantial discomfort and/or a safety hazard and/or vehicle damage requiring a reduction in speed for safety. A higher rating should be assigned to severe corrugations.
Raveling	0-5	0% = 0 (rating) thru 100% = 5 (rating)	———	Raveling is the progressive disintegration of the surface downward. Rate the extent and severity of raveling. Extent is rated relative to the percentage of 200 foot section raveled. Severity is from moderately rough and pitted (largely fine agg.) to severely rough and pitted (includes coarse agg.). A higher rating should be assigned to severe ravelling.
Polished Aggregate	0-5	0% = 0 (rating) thru 100% = 5 (rating)	———	Polished aggregate is present when close examination of a pavement reveals that the portion of aggregate extending above the asphalt is either very small or there are no rough or angular aggregate particles to provide good skid resistance. The extent of polished aggregate is rated relative to the percentage of surface area in 200 foot section denoting and polishing. No degrees of severity are defined.
Overall Riding Quality	0-10	Roughness No. 1600-1750 = 0-3 (rating) Roughness No. 1751-2360 = 4-7 (rating) Roughness No. 2361-5600 = 8-10 (rating)	———	Roughness numbers appears on reverse side and is used to assign rating.

Sum of Defect Ratings ________

Condition Rating = 100 - Sum of Defect Ratings

= 100 - ________

Condition Rating = [ ]

Comments ____

____

Figure 4.1 Flexible Pavement Rating Form Used in Interstate Condition Survey (Continued)

RIGID PAVEMENT RATING FORM

GENERAL COMMENTS

— One rating form is required for each mile of the contract. If the contract is less than one mile only one form is required.

— For each mile a 200 foot long section is chosen, at random, on which the rating is performed. The random section is obtained by the procedure outlined within the table of random numbers. If the contract is dual lane the 200 foot section should be chosen in the travel lane. If the contract is three lanes, as I 465, the 200 foot section should be chosen in the middle lane.

— The separate rating forms should be assimilated and returned to the Research and Training Center within 30 days of receival. Distribution will be made by the Research and Training Center.

GENERAL INFORMATION REQUIRED

District ________________ City or County ________________ Street or Route No ________________

Contract No ________________ Contract Length ________________ Pavement Width ________________ Roughness No ________________

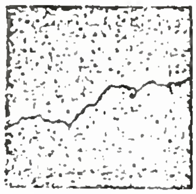
Pavement Type ________________ Age of Pavement ________ ADT ________________ % Trucks ________________ Friction No ________
(i.e., 20' or 40' jointed RCP, PCP, CRC)

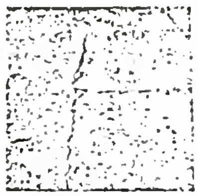
SPECIFIC INFORMATION REQUIRED

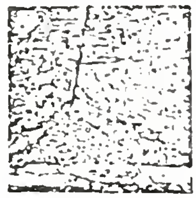
General Location of 200 feet Section within Contract* ________________________________

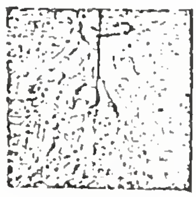
Rating Performed By ________________ Title ________________ Date Performed ________________

*Reference to direction and landmark or distance into contract.

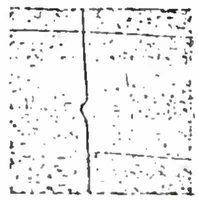

Transverse Cracks

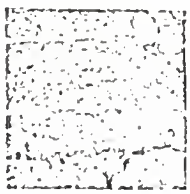

Longitudinal Cracks

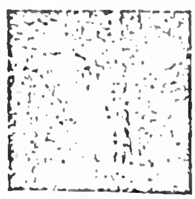

D-Cracking


Crack Spalling


Faulted Transverse Joints


Longitudinal Joint Separation


Patching


Pumping and Water Bleeding

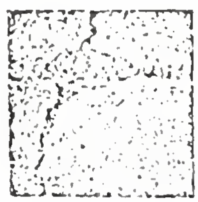

Pavement Breakup

Figure 4.2 Rigid Pavement Rating Form Used in Interstate Condition Survey

DEFECT	RATING SCALE	RATING CRITERIAL BY PAVEMENT TYPE	RATING	DEFECT DESCRIPTION
Transverse Cracks	0-10	20 ft. Jointed PCP or RCP: 0-2 hairline cracks = 0-1 (rating); 3-5 hairline cracks = 2-3 (rating); more than 5 hairline cracks = 4-10 (rating) 60 foot Jointed RCP: 0-2 hairline cracks = 0-1 (rating); 3-5 hairline cracks = 2-3 (rating); more than 5 hairline cracks = 4-10 (rating) CRC: 0-70 hairline cracks = 0-1 (rating); 70-100 hairline cracks = 2-3 (rating); more than 100 hairline cracks = 4-10 (rating)	______	Cracks (not including joints) approximately at right angles to Centerline. Rate the extend severity of cracking. Extent is rated relative to number of cracks in 200 foot section. Severity is rated from hairline cracks (less than 1/8 inch) to severe cracks (greater than ¼ inch). Sealed cracks are rated as hairline cracks unless reopened. Severe cracks should be rated higher than hairline cracks. Cracks less than 18 inches in length are not considered.
Longitudinal Cracks	0-10	0-50 feet of hairline cracking = 0-1 (rating) 51-100 feet of hairline cracking = 2-3 (rating) over 100 feet of hairline cracking = 4-10 (rating)	______	Cracks (not including joints) approximately parallel to the pavement centerline. Rate the extent and severity of cracking. Extent is rated relative to total length of cracks in 200 foot section. Individual cracks are added to obtain estimated total length of cracking. Severity is rated as the average width of crack from hairline (less than 1/8 inch) to severe (greater than ¼ inch). Sealed cracks rated as hairline unless reopened. Severe cracks should be rated higher than hairline cracks. Cracks less than 18 inches in length are not considered.
D-Cracking	0-10	0% = 0 (rating) through 100% = 10 (rating)	______	"D"-cracking is a series of closely spaced crescent shaped hairline cracks that appear at the PCC pavement slab surface adjacent and roughly parallel to joints, cracks, and the free edges of a pavement slab. Rate extent and severity of D-cracking. Extent is rated relative to the percentage of joints and cracks in 200 foot section denoting defect. Severity is rated from light pattern of closely spaced fine cracks that has developed near joints, cracks, and/or free edges, however, width of affected area is generally less than 12 inches wide at the center of the lane, to severe, a high level of spalling at joints/cracks exist and considerable material is loose in affected area. Also width of affected area is generally greater than 12 inches wide at the center of the lane. A higher rating should be assigned to severe D-cracking.
Crack Spalling	0-10	0% = 0 (rating) through 100% = 10 (rating)	______	Breakdown or disintegration of edges of cracks, resulting in the loss of concrete and progressive widening of the cracks. Rate extent and severity of spalling. Extent of crack spalling is rated relative to the percentage of cracks in 200 foot section indicating spalling. Severity is rated from negligible spalling, overall average width less than or equal to ¼ inch, to severe spalling, filled or non-filled cracks, having an overall average spalled width greater than or equal to 1½ inches. A higher rating should be assigned to severe crack spalling.
Faulted Transverse Joints or Cracks	0-10	0 Faults = (0 rating) 1 Fault = (1 rating) 10 or more Faults = 10 (rating)	______	Faulting is a difference of elevation across transverse joints or cracks. Severity of faulting is not measured directly, but is reflected in the overall riding quality. Extent of faulting is rated relative to number of faulted joints or cracks in 200 foot section. Cracks less than 18 inches in length are not considered.
Longitudinal Joint Separation	0-10	See Defect Description	______	Joint separation is the widening of the longitudinal joint between the PCC lanes. Extent and severity of joint separation are not linearly rated since once a joint has opened to ¼ inch wide or wider it has generally been rated. If joint(s) unsealed or not tightly sealed a higher number should be assigned to the defect. (Both joints bounding the lane should be considered)
Patches	0-10	0% = 0 (rating) through 100% = 10 (rating)	______	Patches are temporary or permanent surface repairs to damaged pavement. Rate extent and condition of patching. Rate extent relative to the percentage of pavement surface area in 200 foot section patched. Rate condition of patching from good condition, performing satisfactorily to poor condition, significantly affecting ride quality. A higher rating should be assigned to poor condition patches.
Pavement Breakup	0-10	0% = 0 (rating) through 100% = 10 (rating)	______	Development of cracks in pavement which divide it into two or more pieces. Rate the extent and severity of breakup. Extent is rated relative to the percentage of surface area of 200 foot section that is broken up. Severity is rated relative to the stage of cracking from light pavement breakup which is initial stage cracking to severe pavement breakup which is corner cracking or fragmented pavement. A higher rating should be assigned to severe cracking.
Pumping	0-10	If no pumping is observed rate as 0 If any amount of pumping is observed rate as a 10	______	Pumping is the ejection of water and fine materials under pressure through cracks under moving loads. If pumping exists anywhere in the 200 foot sample unit it is counted as occurring.
Overall Riding Quality	0-10	Roughness No. 2000 - 2250 = 0-3 (rating) Roughness No. 2251 - 2570 = 4-7 (rating) Roughness No. 2571 - 3800 = 8-10 (rating)	______	Roughness number appears on reverse side and is used to assign rating.

Sum of Defect Ratings ______

Condition Rating = 100 - Sum of Defect Rating

= 100 - ______

Condition Rating = $\boxed{}$

Comments ____

____

Figure 4.2 Rigid Pavement Rating Form Used in Interstate Condition Survey (Continued).

Rating Forms

The rating forms developed by IDOH contains all the necessary information to calculate the pavement condition rating (PCR). The forms are self-contained in the sense that there is no need to take a field manual to check the descriptions associated with each potential distress. The rating forms contain photographs of the typical distresses encountered in the pavement network (for example, transverse cracks, alligator cracks, bleeding, and so on). In addition to the typical photographs, a description of each of the distresses is included in the form. The magnitude and severity of the distress are also taken into account in the rating procedure.

For concrete pavements each of the distresses encountered is assigned a defect rating from 0 to 10. The higher the rating of a particular distress, the greater the amount of distress present in the section in question. For flexible pavements, those distresses which are less critical to the overall performance of the pavement structure are assigned a defect rating from 0 to 5 (for example, block cracking, polished aggregate, raveling, and so on).

The criterion used to assign a defect rating of 0 or 10 is a function of the magnitude and severity of the distress.

For example, if rutting is encountered in a pavement section and the rut is at least 20 feet long along the wheelpaths, the following ratings are assigned:

> Rating from 0 to 2 for average rut depth between 1/4 and 1/2 inch;
>
> Rating between 3 and 5 for average rut depth between 1/2 and 3/4 inch;
>
> Rating from 6 to 10 for average rut depth greater than 3/4 inch.

Ruts less than 1/4 inch deep and less than 20 ft long are not rated, therefore, are not considered in the final condition rating.

There are some exceptions, for example, in those cases where pumping is observed, an automatic defect rating of 10 is assigned. Otherwise, no defect rating is recorded.

<u>Pavement Condition Determination</u>

The pavement condition rating for the interstate system was determined using the following equation:

$$PCR = 100 - \sum_{i=1}^{n} D_i \qquad (4.1)$$

where:

PCR = pavement condition rating;

$\sum_{i=1}^{n} D_i$ = sum of the individual defect ratings;

i = distress type;

n = number of distress types encountered in a contract section.

For concrete pavements, all pavement distresses are grouped into ten different types of distresses (see Figure 4.1). For asphalt pavements, thirteen pavement distresses are considered (see Figure 4.2). Both rating procedures take into account the overall riding quality of the pavement section within the 100 point score. The overall riding quality is based upon the roughness number of the section in question at the time the rating was performed.

Crawfordsville Highway District Condition Survey

The Crawfordsville Highway District was selected as the study area for the Federal-aid primary and secondary system condition survey for the following reasons. First, the main goal of this research project was to develop a mathematical model for establishing maintenance priorities to be used by Indiana as part of its pavement management system. The model can be tested using a representative sample of the state

road mileage, and therefore, it is not necessary to include all pavement sections in the Federal-aid primary and secondary system.

Second, as budget for any given fiscal year is allocated by highway district, the smallest possible area to be considered in the model appears to be a district. Since the two organizations associated with the present research are located within the Crawfordsville District (Purdue University and the IDOH Research and Training Center), it was decided to use this District as the study area.

Third, the capabilities of the computer programs currently available at Purdue and used in this research cannot handle the entire state network in one computer run. A highway district was thus considered a feasible unit for the implementation of the model.

Selection of Test Sections

A pavement contract section was used as the smallest sample unit in this research project. For each contract section, the contract length, number and route designation were tabulated according to the current roughness number and pavement age (see Table 4.1). All contract sections classified as old pavements with a high roughness number were initially taken in the sample. The initial trigger value used

Table 4.1 Contract Section Frequency for Each Roughness Number and Pavement Age Combination in the Crawfordsville District.

Age	Roughness Number (Counts per Mile)										
	0-500	501-1000	1001-1400	1401-1800	1801-2000	2001-2300	2301-2500	2501-2700	2701-3000	3001-3500	>3500
0 - 5	8	21	13	10	4	7	1	3	3	1	3
6 - 10	6	19	13	7	4	4	3	0	2	5	0
11- 14	0	3	4	3	4	2	0	2	1	0	1
15- 18	1	7	8	1	2	1	0	0	2	2	0
19- 21	0	1	0	2	3	1	0	0	1	1	1
22- 25	1	0	0	2	0	0	1	0	0	0	2
> 25	0	1	0	1	1	0	0	0	0	0	0

for pavement age was 10 years. The cut-off value used for roughness number was dependent upon the type of pavement evaluated. For concrete pavements, a cut-off value of 2000 was used. For asphalt and overlayed pavements, an initial cut-off value of 1400 was used.

Additional Contract Sections

Several additional contract sections were selected for the pavement condition survey in the Crawfordsville District. These sections were selected independent of the roughness number or the age of the pavement because it was felt that pavement condition index may not be necessarily dependent upon roughness number or age of the pavement section.

The initial reason for selecting pavement sections on the basis of roughness number and pavement age was the need to be consistent with the procedure adopted by the IDOH in the interstate condition survey conducted during the summer 1982.

Delineation of Travel Loops

All selected pavement contract sections were grouped into travel loops originating at West Lafayette. The travel

loops were laid out in such a manner that the farthest contract section was within an 80 mile radius from West Lafayette. Therefore, all pavement sections within a loop can be tested in one day assuming the weather conditions were favorable.

A total of eleven loops were delineated for this task. The entire survey was performed in a two week period since on one day the two travel loops closest to the West Lafayette-Lafayette Area were surveyed. The maps showing the travel loops used in this study along with the pavement contract sections evaluated during the pavement condition survey are shown in Appendix A.

Sampling Procedure

A random sample unit was generated for each contract section. For example, if a particular contract section was 6.4 miles long, a random number between 1 and 64 was generated. This number corresponded to the distance from the start of the section to the sample unit in question. However, before a sample unit was finally selected, a visual check was made by driving through the entire section to see if it was homogeneous and also to verify if the sample unit was truly representative of the present condition of the contract section in question. If this was not the case, another random sample unit was generated. In this survey

additional sample units were required only on those pavement segments which were close to an intersection passing through a town or village.

For asphalt pavements, a sample unit was specified as 100 ft. long and 24 ft. wide. For concrete pavements, a sample unit included 20 slabs with a slab spacing of about 30 ft. In those sections with joint spacing greater than 30 ft., an imaginary joint was assumed at the middle of the span. In most cases the spacing was about 40 ft. and a transverse crack had already developed at mid-span. This crack was then assumed as the imaginary joint.

Rating Forms Description

The rating forms developed by the U.S. Army Construction Engineering Research Laboratory (CERL) were used to record the distresses for both asphalt and concrete pavements. These forms are shown in Figures 4.3 and 4.4 for asphalt and concrete pavements, respectively.

The rating manual developed by CERL was required during the condition survey. It contains a description of each of the distress types including typical photographs at different severity levels. The deduct curves for each of the pavement distresses and the adjustment curves for both asphalt and concrete pavements are included in the rating

ASPHALT PAVEMENT INSPECTION SHEET

BRANCH ______________ SECTION ______________

DATE ______________ SAMPLE UNIT ______________

SURVEYED BY ______________ AREA OF SAMPLE ______________

Distress Types

1. Alligator Cracking	*10. Long & Trans Cracking
2. Bleeding	11. Patching & Util Cut Patching
3. Block Cracking	12. Polished Aggregate
*4. Bumps and Sags	*13. Potholes
5. Corrugation	14. Railroad Crossing
6. Depression	15. Rutting
*7. Edge Cracking	16. Shoving
*8. Jt Reflection Cracking	17. Slippage Cracking
*9. Lane/Shldr Drop Off	18. Swell
	19. Weathering and Raveling

SKETCH:

EXISTING DISTRESS TYPES

TOTAL SEVERITY L						
M						
H						

PCI CALCULATION

DISTRESS TYPE	DENSITY	SEVERITY	DEDUCT VALUE
DEDUCT TOTAL			
CORRECTED DEDUCT VALUE (CDV)			

PCI = 100 - CDV =

RATING =

* All Distresses Are Measured In Square Feet Except Distresses 4,7,8,9 and 10 Which Are Measured In Linear Ft; Distress 13 Is Measured In Number of Potholes.

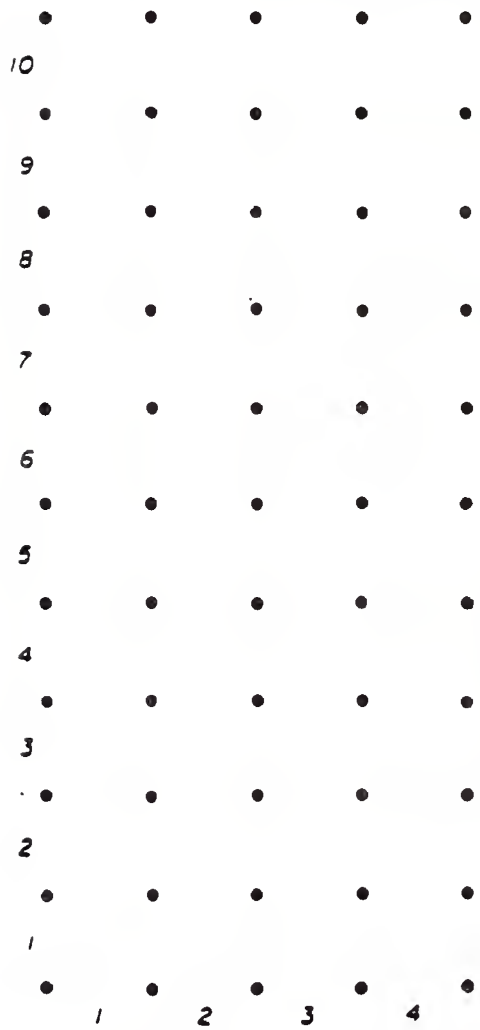
Figure 4.3 Flexible Pavement Rating Form Used In Crawfordsville District Condition Survey. [33]

CONCRETE PAVEMENT INSPECTION SHEET

BRANCH ________________ SECTION ____________

DATE ________________ SAMPLE UNIT ____________

SURVEYED BY ________________ SLAB SIZE ____________



Distress Types

21. Blow-Up Buckling/Shattering
22. Corner Break
23. Divided Slab
24. Durability ("D") Cracking
25. Faulting
26. Joint Seal Damage
27. Lane/Shldr Drop Off
28. Linear Cracking
29. Patching, Large & Util Cuts
30. Patching, Small
31. Polished Aggregate
32. Popouts
33. Pumping
34. Punchout
35. Railroad Crossing
36. Scaling/Map Cracking/Crazing
37. Shrinkage Cracks
38. Spalling, Corner
39. Spalling, U Joint

DIST. TYPE	SEV.	NO. SLABS	% SLABS	DEDUCT VALUE
26 *				
DEDUCT TOTAL				
CORRECTED DEDUCT VALUE (CDV)				

PCI = 100 - CDV = ________

RATING = ________

* All Distresses Are Counted On A Slab-By-Slab Basis Except Distress 25, Which Is Rated For the Entire Sample Unit.

Figure 4.4 Rigid Pavement Rating Form Used In Crawfordsville District Condition Survey. [33]

manual along with the steps for computing the pavement condition index (PCI).

<u>Pavement Condition Determination</u>

The Pavement Condition Index (PCI) developed by Shahin was used as the indicator of the present pavement condition [33]. This method is based on deduct values which are a function of the types, severities, and densities of visible distresses.

The model used to represent the PCI is as follows:

$$PCI = 100 - \left[\sum_{i=1}^{p} \sum_{j=1}^{m_i} a(T_i, S_j, D_{ij}) \right] F(t,q) \qquad (4.2)$$

where:

PCI = pavement condition index;

a( ) = a weighted deduct value which depends on the type of distress T_i, severity level S_j, and distress density D_{ij};

i = counter for distress types;

j = counter for severity levels;

p = total number of distress types for the pavement type under consideration;

m_i = number of severity levels on the i^{th} type of distress;

F(t,q) = an adjustment function for multiple distresses which vary with the total summed deduct value (t) and number of deducts (q).

The steps used in this study to determine the PCI are shown in Figure 4.5 and summarized below:

1. Divide the contract section into sample units

2. Inspect each sample unit and determine the types of distresses and severity levels associated to each distress. Measure the extent (density) associated to each distress type, severity level and density combination.

3. Compute the total deduct value for each sample unit (TDV).

4. Adjust the total deduct value (CDV) using the adjustment function applicable to each sample unit. The adjustment function is dependent on the number of entries with deduct values over 5 points as well as the total deduct value (TDV).

5. Compute the pavement condition index for each sample unit by subtracting the corrected deduct value from 100 [PCI=100 - CDV].

6. Compute the PCI of the entire contract section by taking the average of the PCI's sample units.

7. Determine the pavement condition rating of the contract section (i.e. Excellent, Very Good, Good, Fair, Poor, Very Poor, Failed)

Asphalt pavements, overlay pavements, and jointed reinforced concrete pavements within the Crawfordsville District were evaluated using the afore-mentioned procedure.

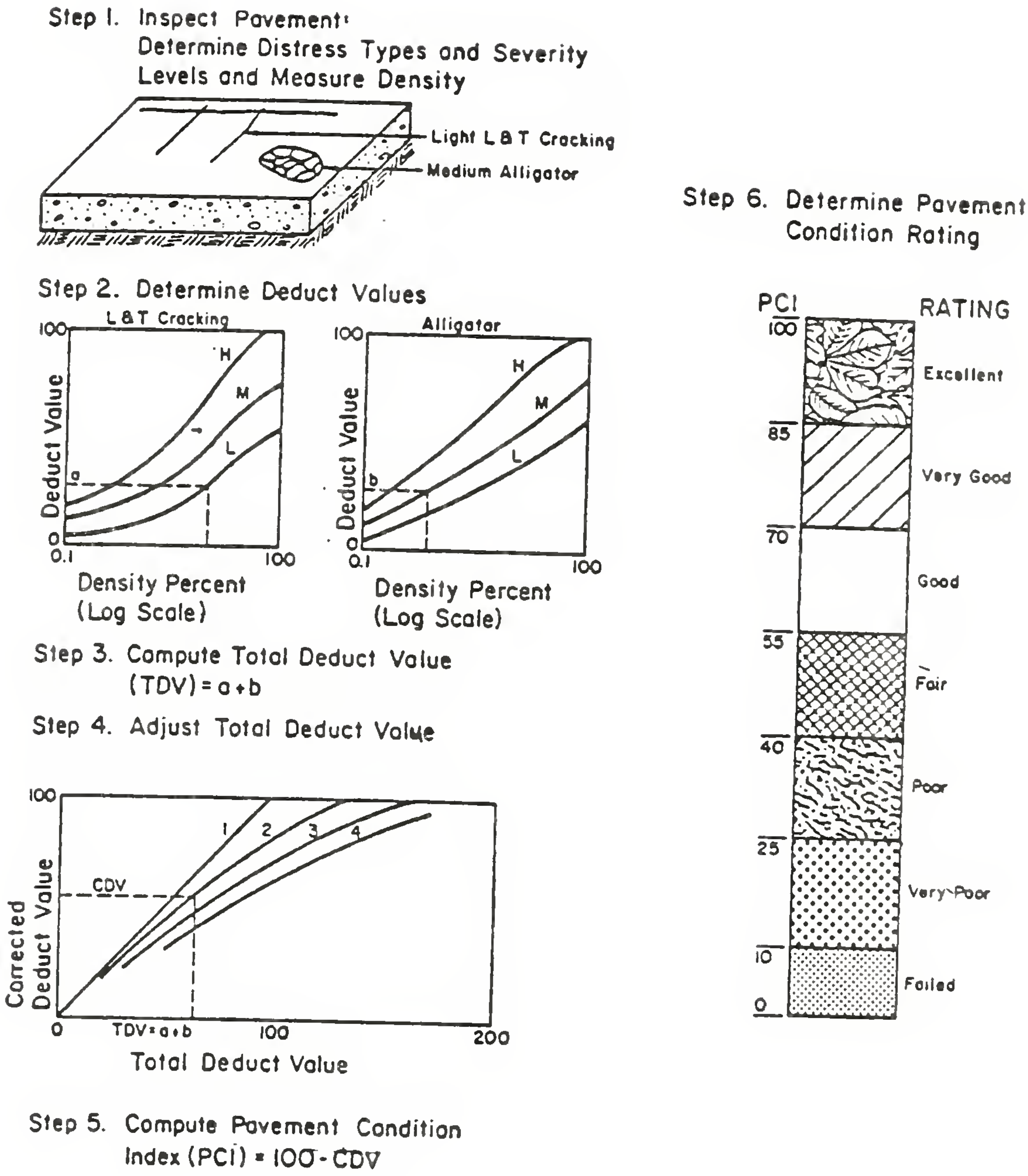


Figure 4.5 Steps for Calculating the Pavement Condition Index. [33]

Equipment Used

The equipment used during the pavement condition survey consisted of an odometer wheel, 8 ft. straight-edge, the inspection forms, and the PCI distress guide.

The hand odometer was used in asphalt pavements to measure the lengths and area associated to each distress. It was also used to measure the length and width of the sample section in question.

The 8 ft. straight-edge was used in conjunction with a ruler to measure faulting and lane/shoulder drop-off in concrete pavements. In asphalt pavements it was used to measure the depth of ruts as well as depressions.

The PCI distress guide developed by the Construction Engineering Research Lab (CERL) was required during the condition survey since each distress type has different severity levels (low, medium, high) and different means to measure the extent of the distress (i.e. linear feet, square feet, number of potholes, and so on).

Analysis of Pavement Condition Data

Interstate Condition Survey

The pavement condition rating was computed for 247 pavement sections within the Interstate system, of which 241 were jointed reinforced and continuously reinforced concrete pavement sections and the remaining six were flexible pavement sections primarily overlayed sections. All the concrete contract sections having a roughness number greater than 2000 as well as all the flexible pavement sections with roughness number greater than 1400 were evaluated.

For ease of understanding, the discussion of the results of the interstate condition survey was divided into three sections. The first two sections describe the results applicable to the 241 jointed reinforced and continuously reinforced concrete pavement sections surveyed. The third section discusses the results pertaining to the flexible pavement sections surveyed.

Discussion of Results

JRC Pavements: Figure 4.6 shows the distribution of the pavement condition rating for the jointed reinforced concrete pavements evaluated in this condition survey. It is interesting to note that over 68 percent of the concrete

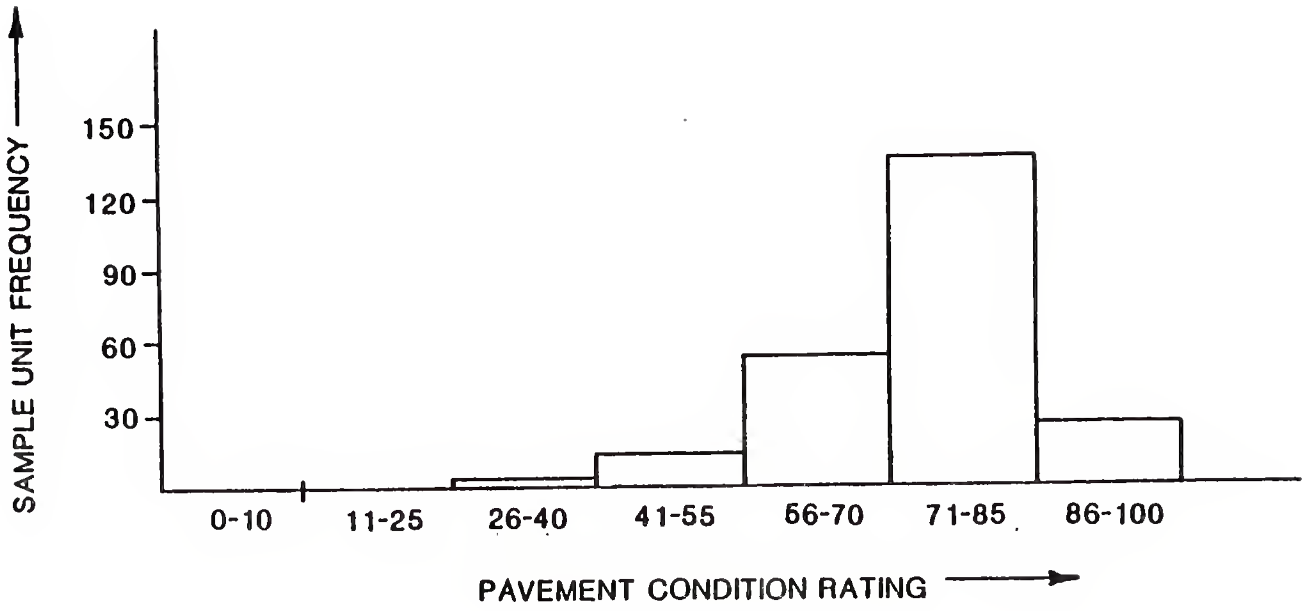


Figure 4.6 Distribution of Pavement Condition Rating (PCR) for Jointed Reinforced Concrete Pavements in the Interstate System.

pavement sections which have a roughness number greater than 2000 counts per mile thus, in fact, have a pavement condition rating greater than 70. In other words, the surface condition of most of the interstate concrete pavement sections surveyed are, in a sense, in fairly good condition. This implies that rough pavement surfaces are not necessarily those pavements which are severely distressed. This brings out the importance of conducting a complete pavement condition survey in the implementation of a pavement management system for Indiana. Roughness measurements by itself, is not a good indicator of the overall structural condition of the pavement. The importance of a complete pavement condition survey cannot be overemphasized.

In order to know the magnitude and severity of each of the pavement distresses encountered on pavements in the state of Indiana, a series of histograms have been constructed and discussed in the following sections.

Figures 4.7 shows the distribution of the pavement distresses encountered on the jointed reinforced concrete pavement sections evaluated in this study. Figures 4.8 through 4.16 show the defect rating distributions for each individual pavement distress.

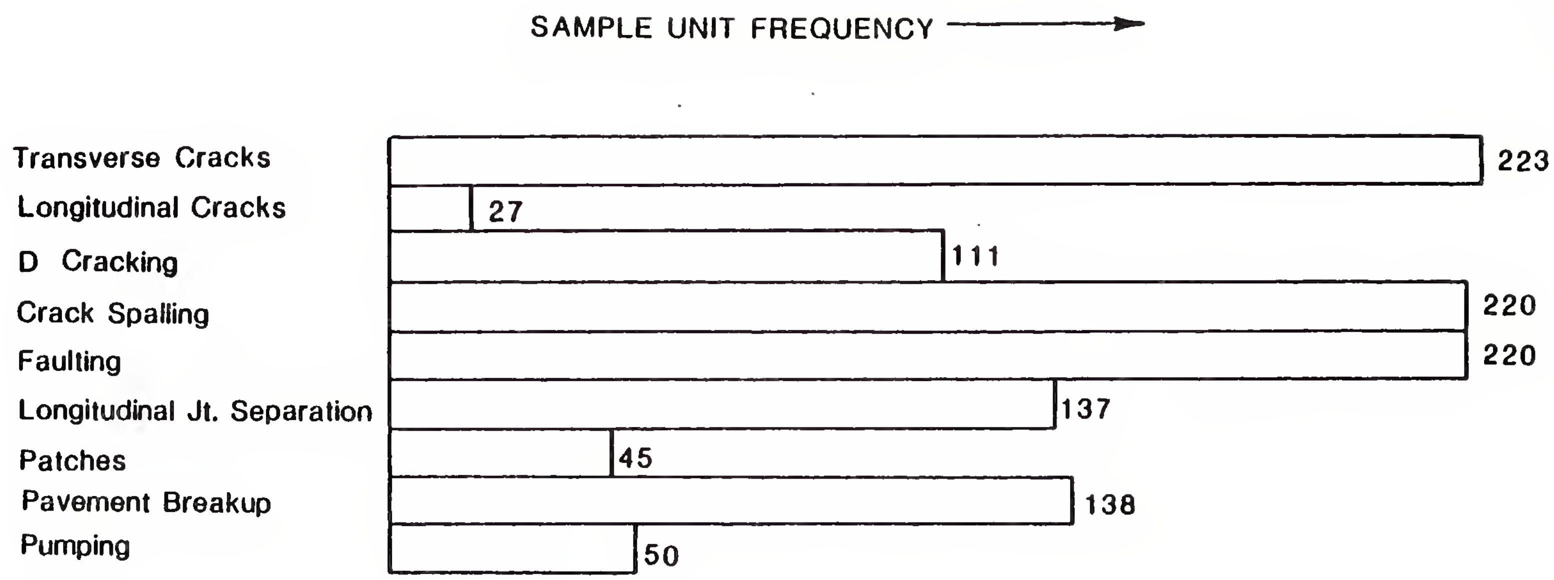


Figure 4.7 Distribution of Pavement Distresses in Jointed Reinforced Concrete Pavements in the Interstate System.

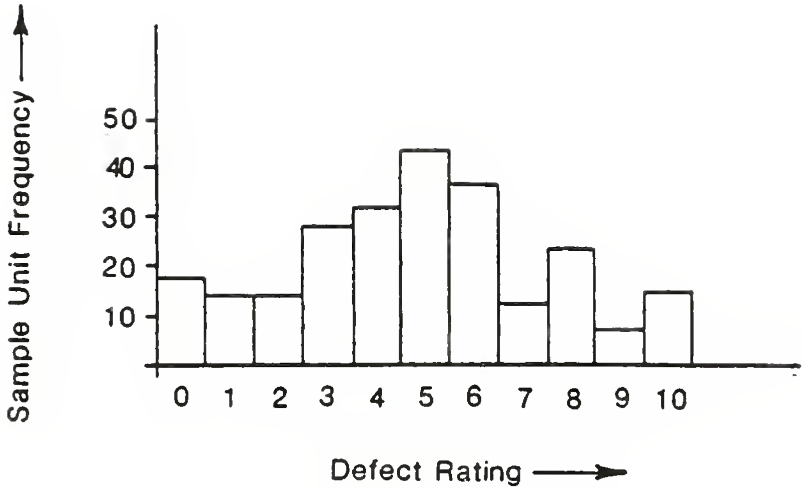


Figure 4.8 Defect Rating Distribution for Faulting.

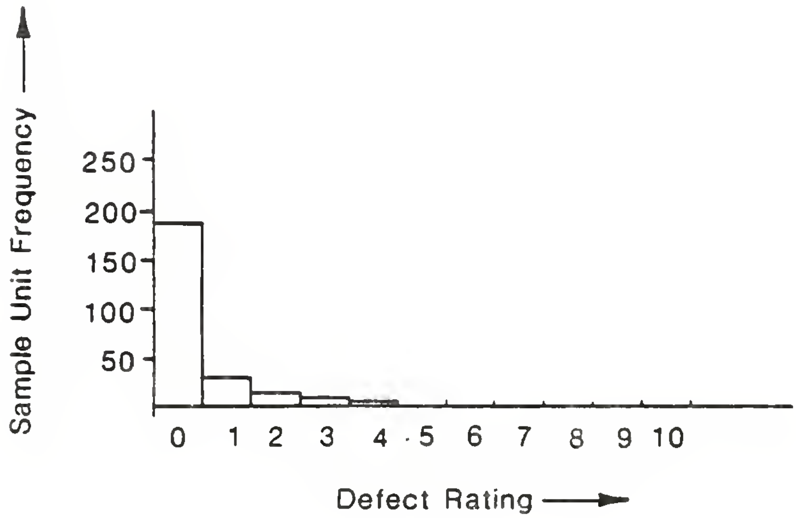


Figure 4.9 Defect Rating Distribution for Patching.

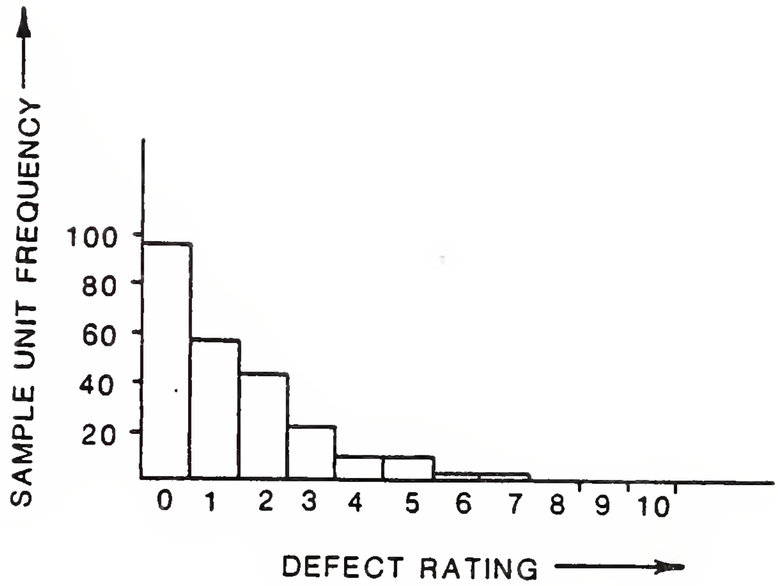


Figure 4.10 Defect Rating Distribution for Longitudinal Joint Separation.

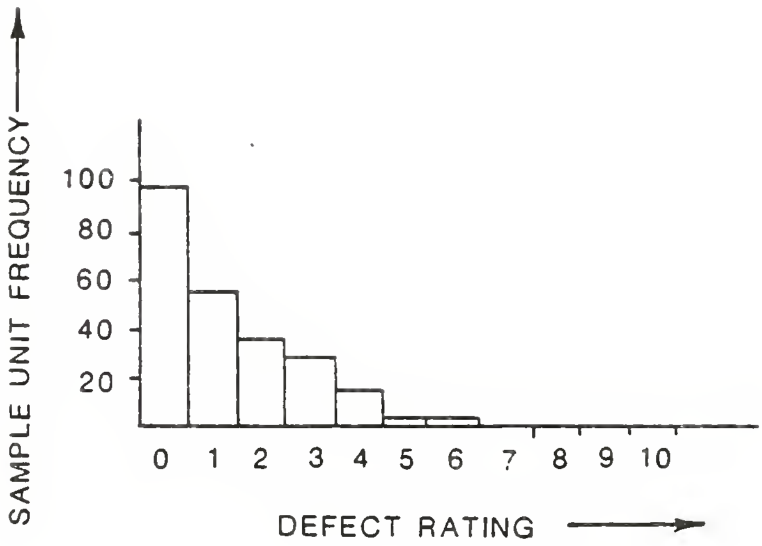


Figure 4.11 Defect Rating Distribution for Pavement Breakup.

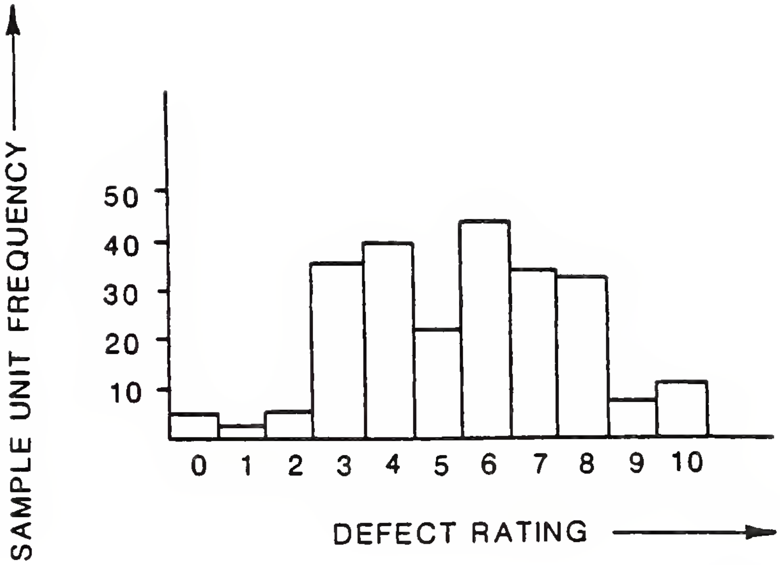


Figure 4.12 Defect Rating Distribution for Transverse Cracks.

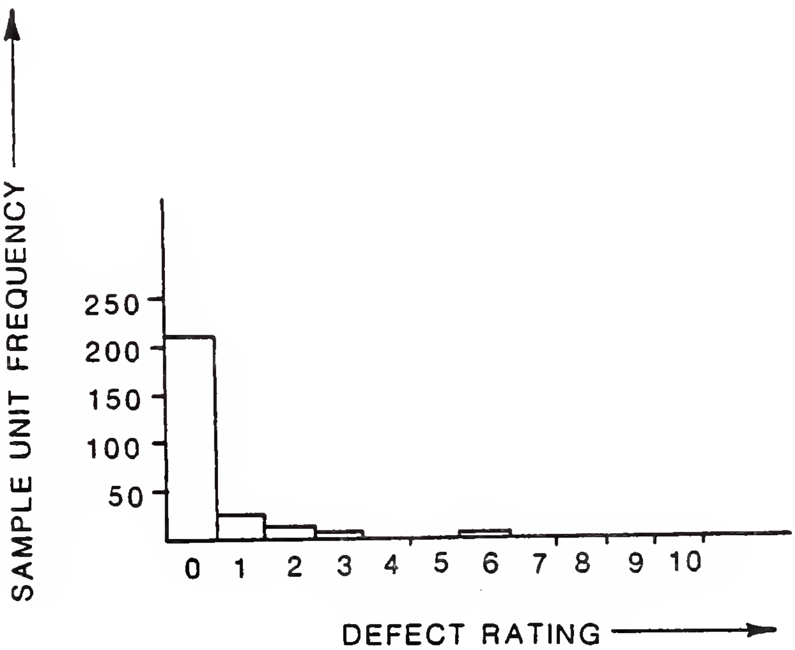


Figure 4.13 Defect Rating Distribution for Longitudinal Cracks.

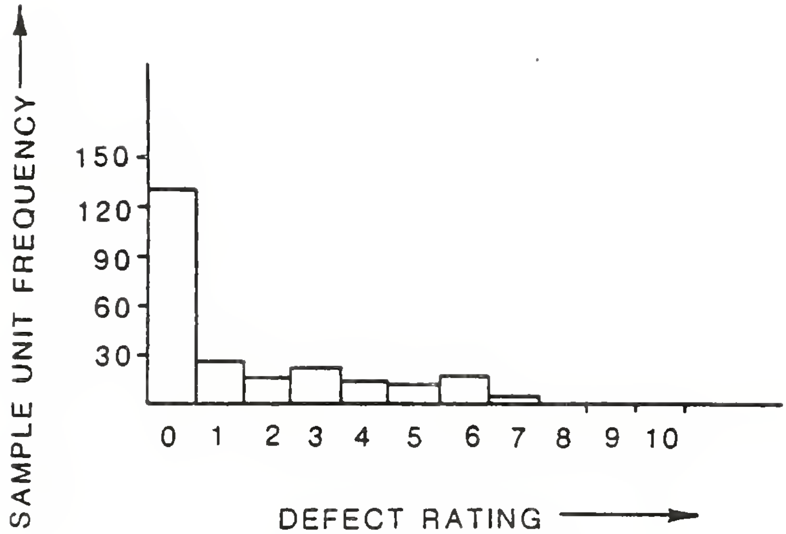


Figure 4.14 Defect Rating Distribution for Durability Cracks.

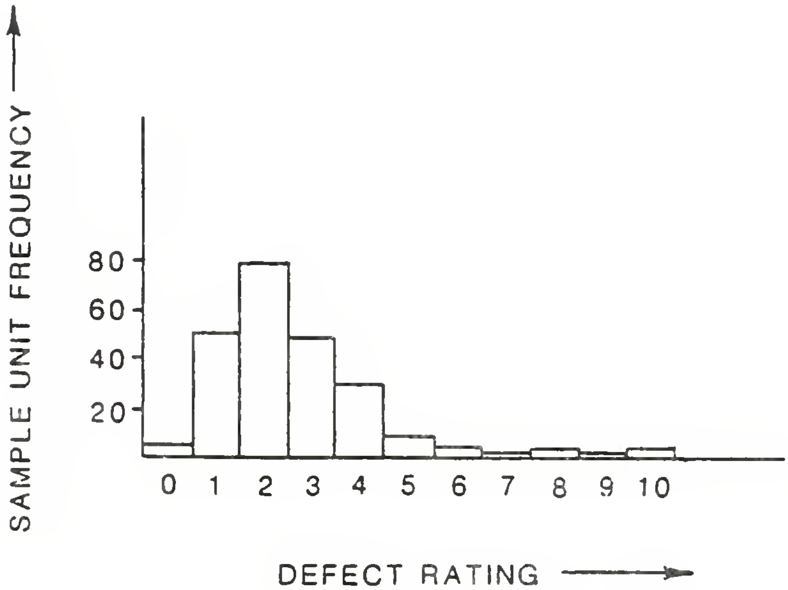


Figure 4.15 Defect Rating Distribution for Spalled Cracks.

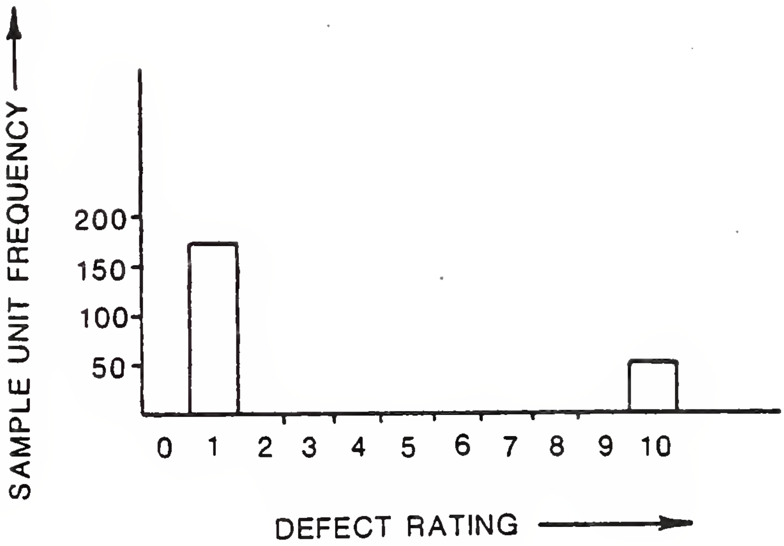


Figure 4.16 Defect Rating Distribution for Pumping.

The most important aspects of these distributions are summarized below:

1. Over 98 percent of the pavement sections which have a roughness number greater than 2000 thus in fact have faulted joints or cracks. Faulting appears to be quite severe since sixty-percent of these pavement sections were assigned a defect rating of at least five on a global scale of ten (see Figure 4.8).

2. Patches were encountered in less than 20 percent of the pavement sections surveyed. In addition, they appear to be in very good structural condition since none of them was given a defect rating greater than five (see Figure 4.9).

3. Longitudinal joint separation does not appear to be a significant factor in the high roughness readings encountered in the pavement sections surveyed since only 4 percent of the sections were assigned a defect rating of greater than five, and 83 percent of the sections assigned a defect rating of 2 or less (see Figure 4.10).

4. Pavement breakup was not considered to be critical in the high roughness readings since less than three percent of the sections have a defect rating greater than or equal to five (see Figure 4.11).

5. As expected, transverse cracks were encountered on almost every pavement section surveyed. The distribution of the transverse cracks in these sections follow a normal distribution with about 60 percent of the sections have been assigned a defect rating of at least five (see Figures 4.12).

6. Longitudinal cracks were only encountered on twelve percent of the sections and the defect rating assigned to them was always less than three (see Figure 4.13).

7. Durability cracks were encountered on fifty percent of the pavement sections evaluated but, only 15 percent of them have been assigned a defect rating greater than or equal to five (see Figure 4.14).

8. Spalled cracks were present on almost every pavement section surveyed, however, only 9 percent were assigned a defect rating greater than five (see Figure 4.15).

9. Evidence of pumping was present on 22 percent of the pavement sections surveyed. All of these sections were assigned an automatic defect rating of 10. (see Figure 4.16).

CRC Pavements: Thirteen continuously reinforced concrete pavement sections were evaluated as part of the interstate condition survey. The pavement condition rating distribution is shown in Figure 4.17. Over ninety percent of the CRC pavement sections have been assigned a pavement condition rating of at least 70. Figure 4.18 shows the frequency distribution of the pavement distresses encountered in the CRC pavement sections evaluated. The defect rating distributions for each individual pavement distress encountered in CRC pavements are also shown in Figures 4.19 through Figure 4.26.

The most important aspects of the defect rating distributions are summarized below:

1. Longitudinal cracks were encountered on over 60 percent of the pavement sections surveyed. However, the defect rating assigned to them was in most cases, less than two (see Figure 4.19).

2. Spalled cracks were present in almost every pavement section evaluated. As it was the case for longitudinal cracks, the defect rating assigned to them was in most cases, less than or equal to two (see Figure 4.20).

3. Longitudinal joint separation was present in over 60 percent of the sections evaluated however, only one section had a defect rating greater than five (see Figure 4.21).

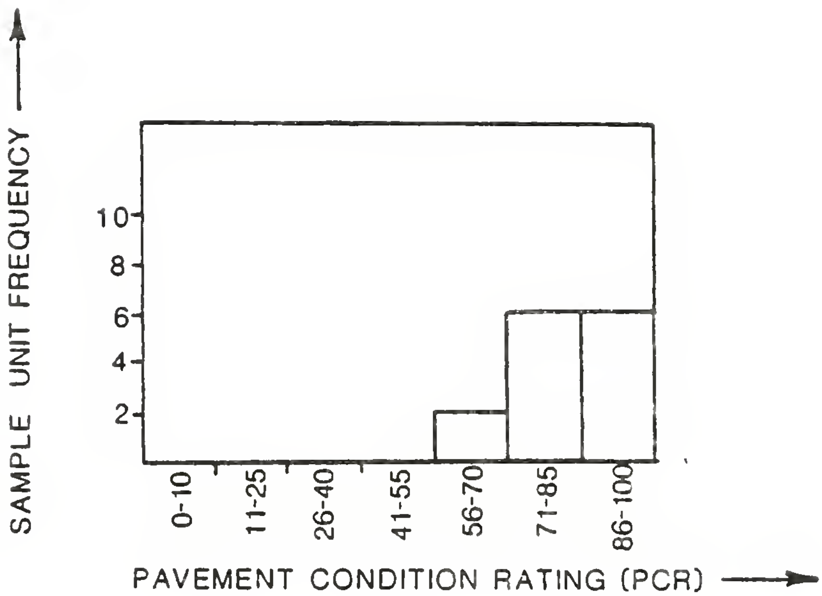


Figure 4.17 Distribution of Pavement Condition Rating (PCR) for Continuously Reinforced Concrete (CRC) Pavements in the Interstate System.

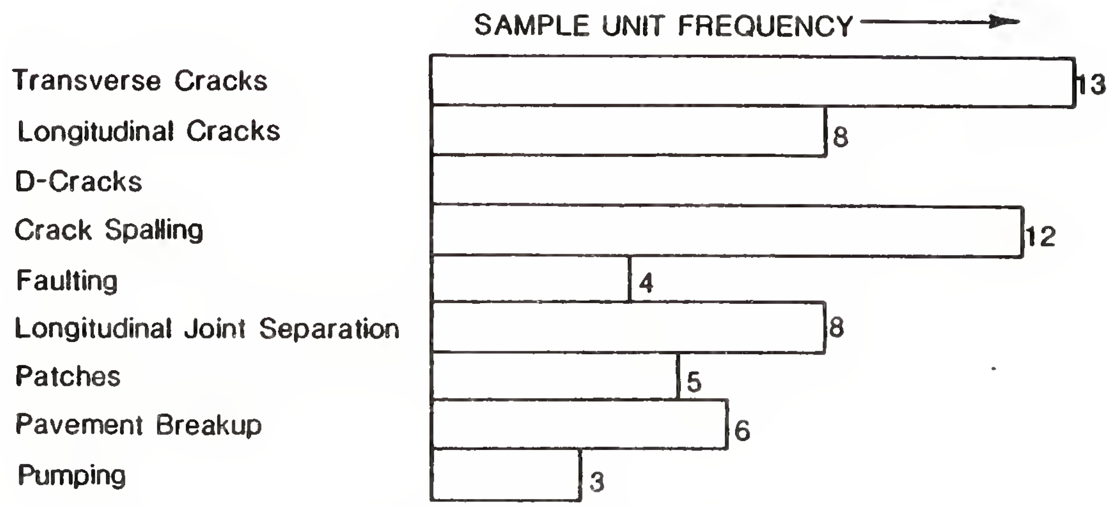


Figure 4.18 Distribution of Pavement Distresses in Continuously Reinforced Concrete (CRC) Pavements in the Interstate System.

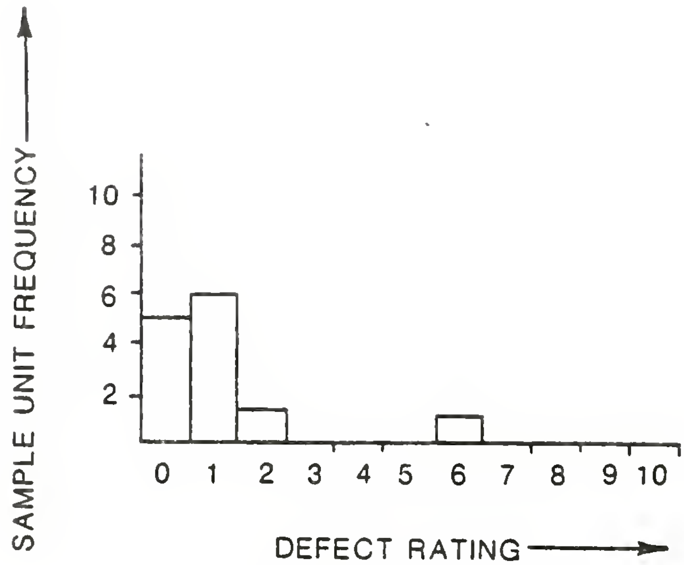


Figure 4.19 Defect Rating Distribution for Longitudinal Cracks.

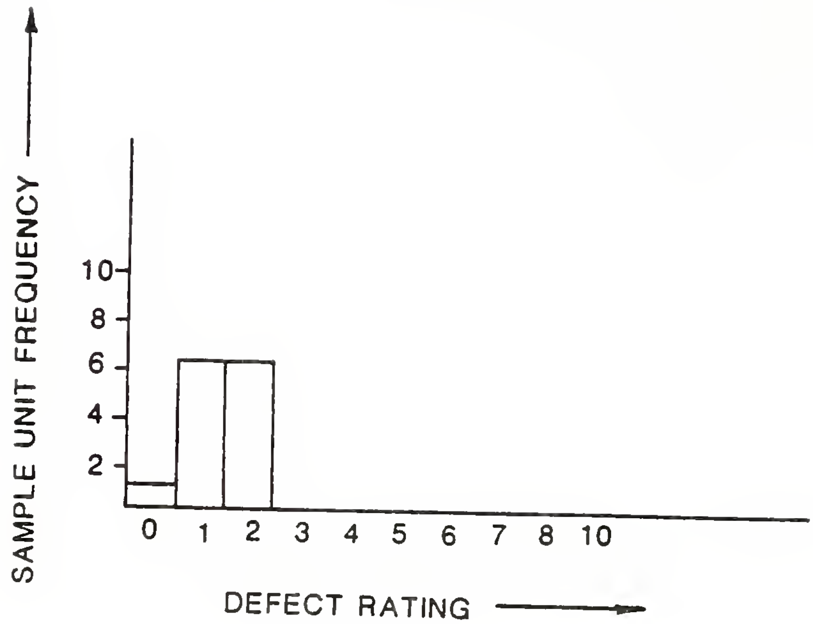


Figure 4.20 Defect Rating Distribution for Crack Spalling.

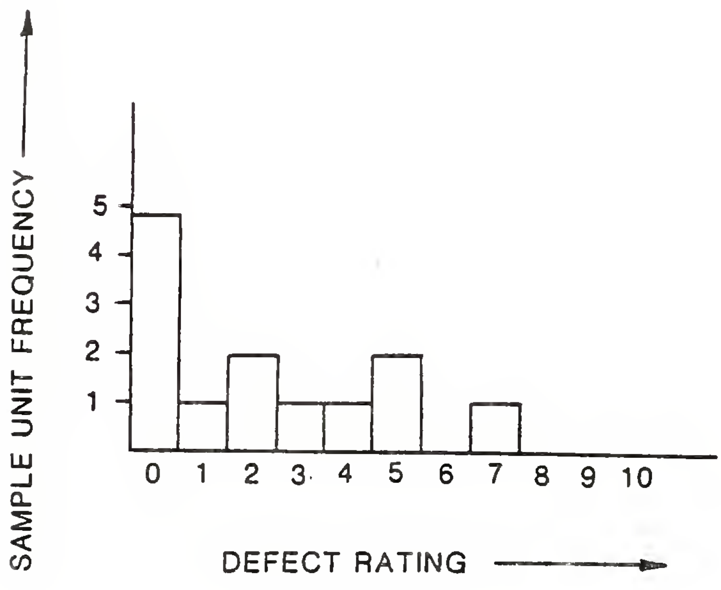


Figure 4.21 Defect Rating Distribution for Longitudinal Joint Separation.

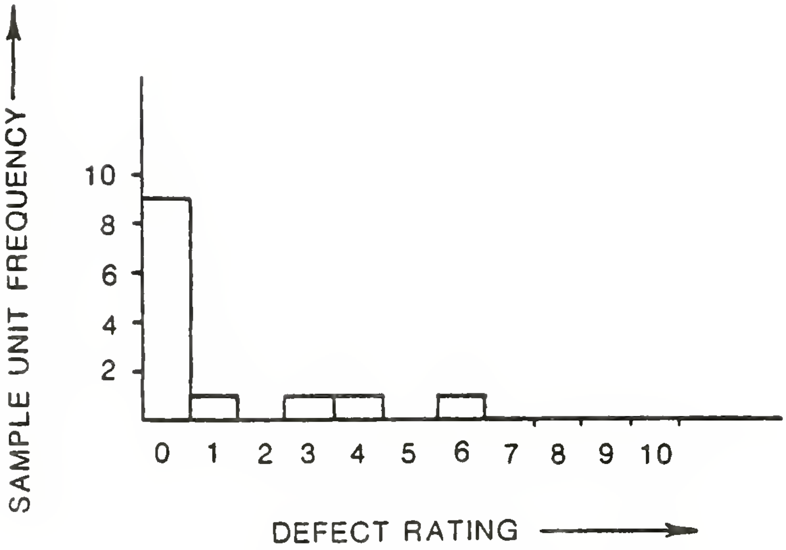


Figure 4.22 Defect Rating Distribution for Faulting.

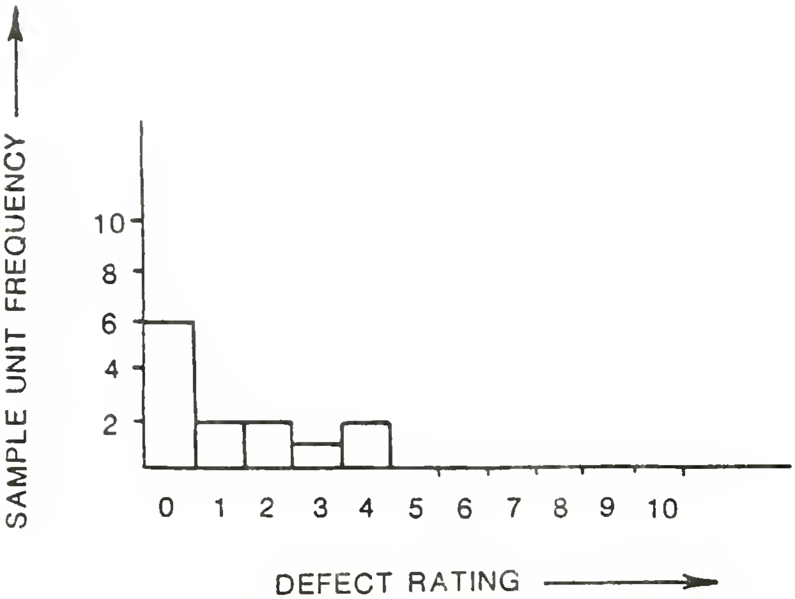


Figure 4.23 Defect Rating Distribution for Patches.

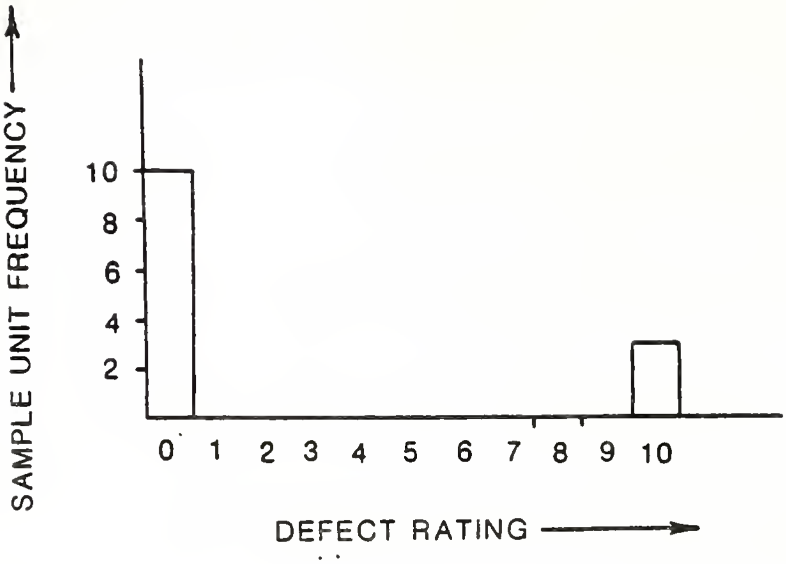


Figure 4.24 Defect Rating Distribution for Pumping.

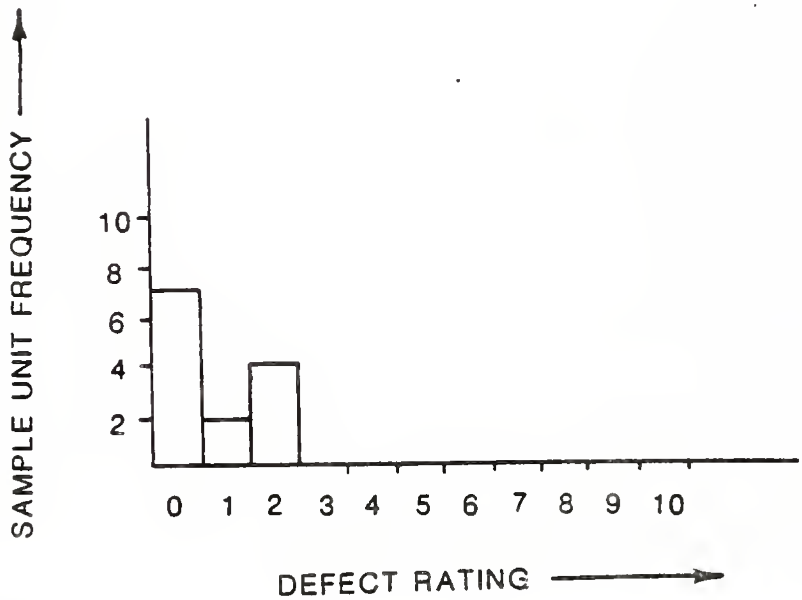


Figure 4.25 Defect Rating Distribution for Pavement Breakup.

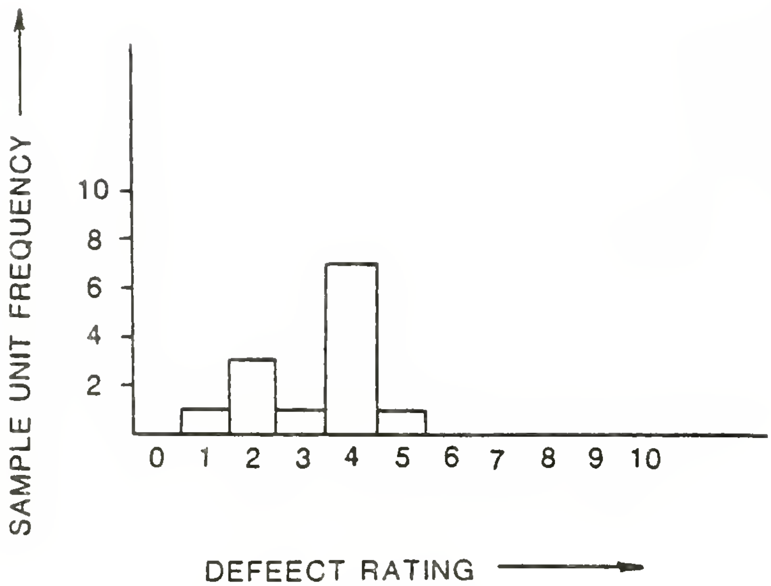


Figure 4.26 Defect Rating Distribution for Transverse Cracks.

4. Durability cracks were not present in any of the CRC pavement sections evaluated.

5. Faulting was not a critical distress, neither pavement breakup even though it was present in 46 percent of the test sections (see Figure 4.22).

6. Patches were present in almost 40 percent of the pavement sections, however, none of them is considered to be severely distressed (see Figure 4.23).

7. Three of the thirteen sections show evidence of pumping, primarily at the pavement edges (see Figure 4.24).

8. Pavement Breakup was present on 46 percent of the sections but, the defect rating assigned was always less than two (see Figure 4.25).

9. Transverse cracks were present on all CRC sections evaluated with the majority of the sections been assigned a defect rating of four (see Figure 4.26).

Flexible Pavements: In Indiana's interstate system, most of the sections classified as flexible pavements are jointed reinforced concrete pavements which have been overlayed within the last eight years. Several full depth asphalt pavement sections are also considered within this category.

Only five flexible pavement sections were encountered which have a roughness number greater than 1400. All of the five sections were assigned a pavement condition rating of at least 80, with an average rating of about 83. Rutting was the major source of distress in two of the five sections, while patches and pumping were the other major distresses encountered in two of the three remaining sections.

The defect rating assigned to them was 6 and 10, respectively. The remaining sections did not have a major distress present since the highest defect rating assigned was never greater than three.

Pavement Condition Rating Prediction

An attempt was also made to predict the pavement condition rating using roughness measurements, pavement age, and current traffic (ADT) as the independent variables. The regression model developed for this purpose is of the following form:

$$PCR = 126.22 - 0.00035*ADT - 0.0143*RN - 0.725*AGE \quad (4.3)$$

where:

PCR = pavement condition rating;

ADT = average daily traffic in one direction;

RN = roughness number in counts per mile;

AGE = pavement age (1982 - year opened to traffic).

In this model, pavement age appears to be the most significant independent variable in predicting the pavement condition rating.

If the age of the pavement section is not known, the following model can be used:

$$PCR = 109.986 - 0.00005*ADT - 0.0136*RN \qquad (4.4)$$

A simplified regression model was also developed to estimate the pavement condition rating based only on roughness measurements. This is shown below:

$$PCR = 109.53 - 0.136*RN \qquad (4.5)$$

A regression model to estimate pavement condition rating as a function of pavement age and roughness number is also shown below:

$$PCR = 118.25 - 0.464*AGE - 0.014*RN \qquad (4.6)$$

In this model the effect of pavement age in estimating the pavement condition rating is evident.

It is not the purpose of this research project to conduct a comprehensive statistical analysis on the effect of roughness, traffic, and pavement age on the pavement condition rating but, to show the importance of collecting pavement condition data in conjunction with roughness measurements as part of IDOH pavement monitoring program. The regression equations included in this section should only be considered as a guide. Even though a correlation exists between pavement condition rating, pavement age, and traffic, it is not a strong relation that can be used to make investment decisions.

The primary reason for conducting the condition survey was to show the importance of the pavement condition rating in the overall pavement management process. This parameter should be considered in the optimization program.

Crawfordsville Highway District

The pavement condition index (PCI) was determined on 111 of the 115 sample pavement sections initially chosen using the procedure explained in the PCI distress guide developed by CERL. Of the 111 test sections, 90 were grouped as asphalt and overlayed pavements and the remaining 21 sections were classified as concrete pavements. Four test sections were eliminated since they were resurfaced.

Discussion of Results

Asphalt Pavements: The distribution of the pavement condition index for flexible pavement sections evaluated in this study is shown in Figures 4.27. It is interesting to note that even though most of the pavement sections are very rough (i.e. RN > 2000) and relatively old (i.e. age > 10 years), the majority of the pavements evaluated are in a sense, in good surface condition. In other words, pavement condition index for the pavements located in the Crawfordsville Highway District is relatively high taking into account the sampling procedure was based primarily on

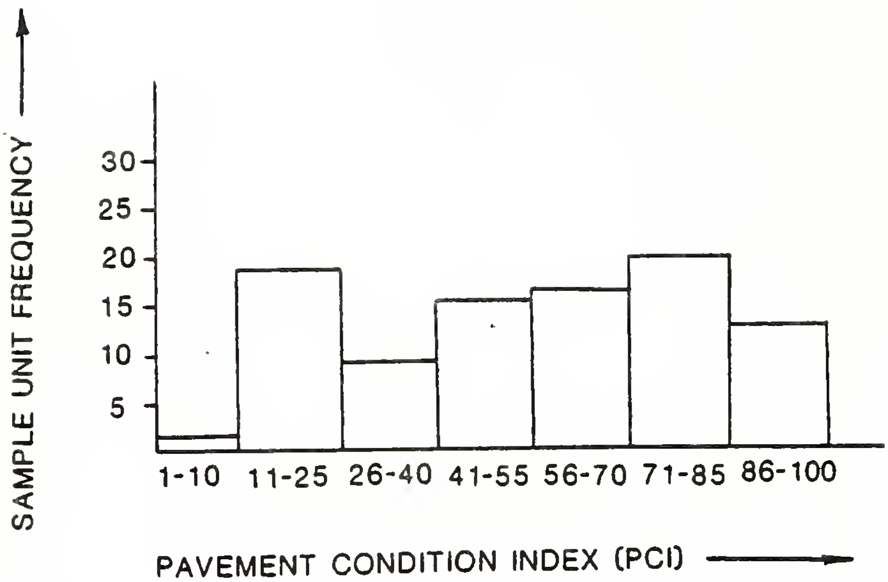


Figure 4.27 Distribution of Pavement Condition Index (PCI) for Flexible Pavement Sections Evaluated in the Crawfordsville Highway District.

sections which have a high roughness level as well as relatively old as compared to the entire pavement population.

Figure 4.28 shows the distribution of the flexible pavement distresses in the Crawfordsville Highway District. Figure 4.29 shows a further breakdown of each of the pavement distress according to the severity of the distress in question. Figures 4.30 through 4.45 show the deduct value distribution for each individual distress. As the deduct value increases, the magnitude and severity of the distress in question increases as well. In the interstate condition survey the defect rating was used as the measure of the magnitude and severity of each distress. In this case as the defect rating increases, the distress in question becomes more critical.

The most important aspects of the deduct value distributions are discussed below:

1. Alligator cracks were encountered on 41 percent of the pavement sections surveyed. On only twelve percent of these sections the distress were classified as medium severity. However, due to the magnitude and extent of the distress, over 55 percent of the these sections were assigned a deduct value of at least 30 (see Figure 4.30).

2. Bleeding was present on 34 percent of the pavement sections, of which 16 percent experience severe bleeding. However, only 8 percent of these sections were assigned a deduct value greater than 40 (see Figure 4.31).

3. Rutting was encountered on 49 percent of the pavement sections evaluated. On 40 percent of these sections

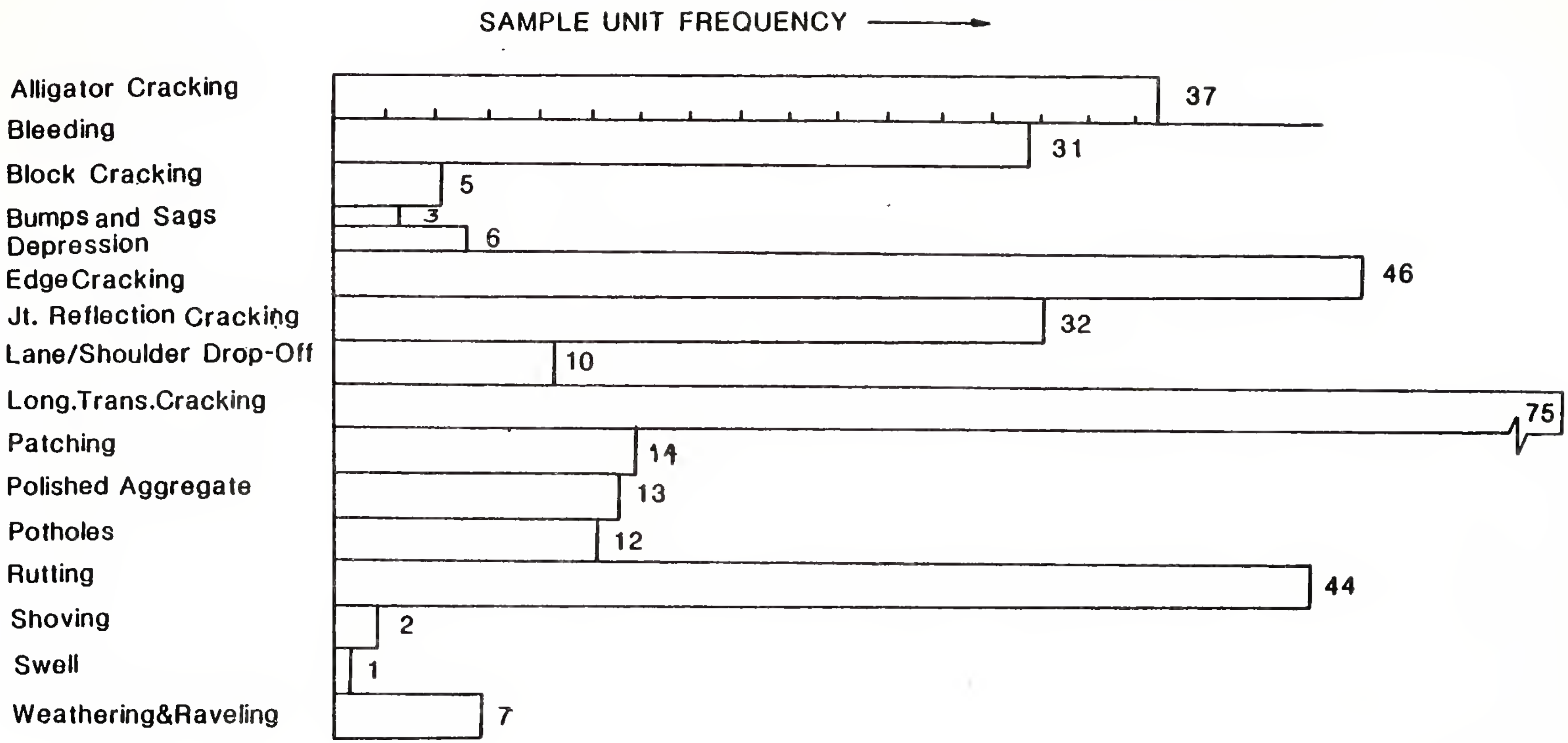
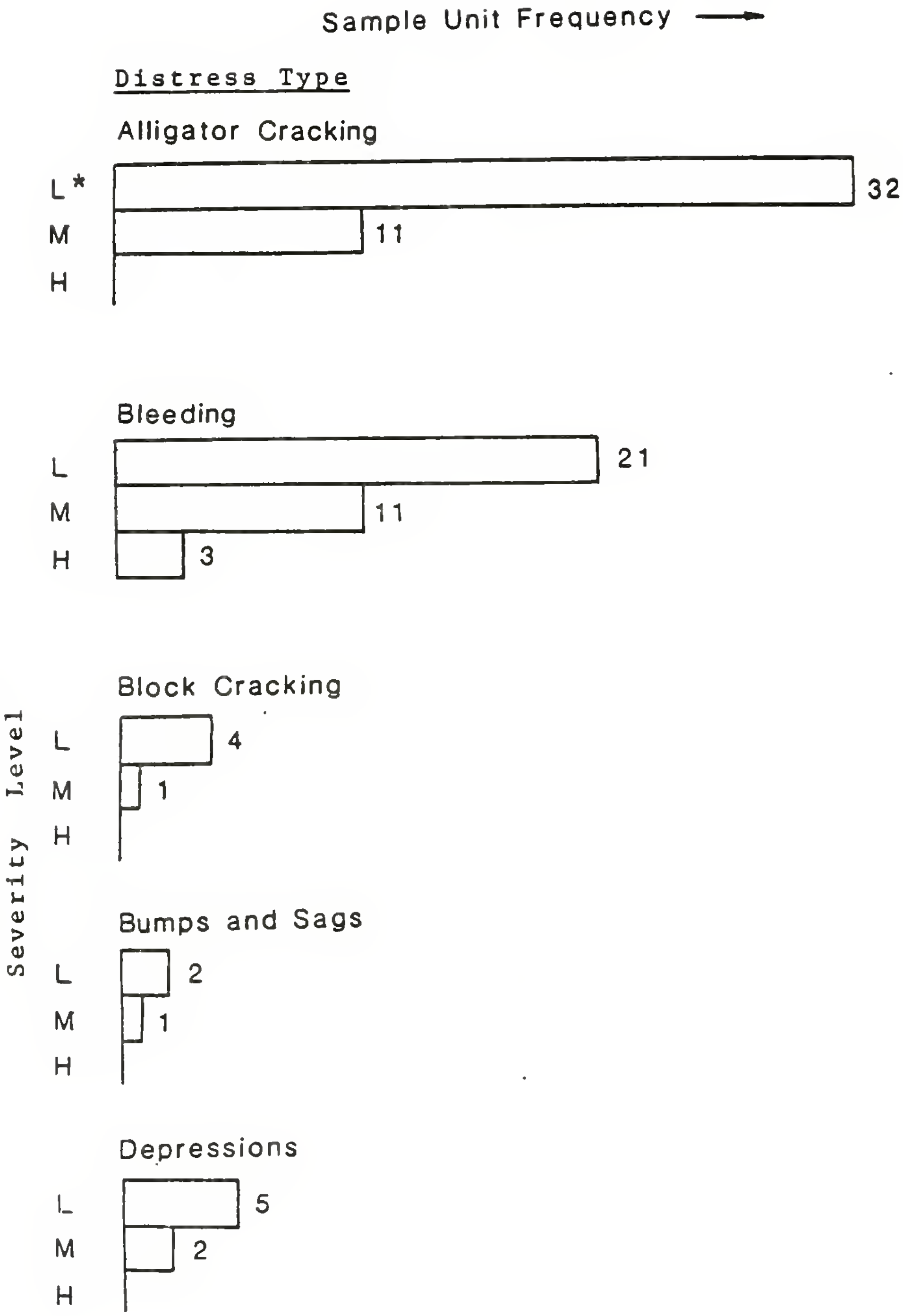


Figure 4.28 Distribution of Asphalt Pavement Distresses in the Crawfordsville Highway District.



*L = Low, M = Medium, and H = High.

Figure 4.29 Distribution of Flexible Pavement Distresses in the Crawfordsville Highway District According to Severity Level.

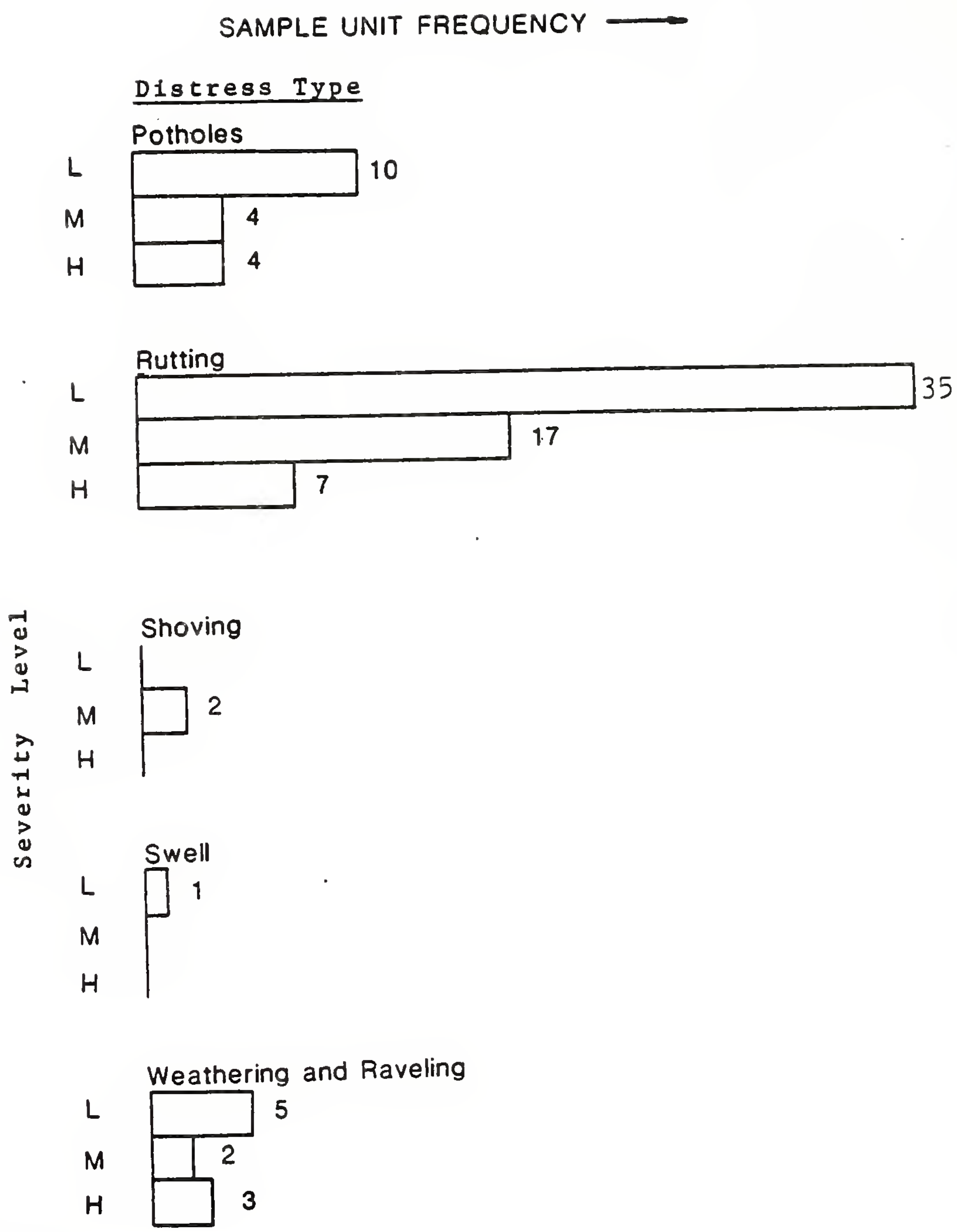


Figure 4.29 Distribution of Flexible Pavement Distresses in the Crawfordsville Highway District According to Severity Level (Continued).

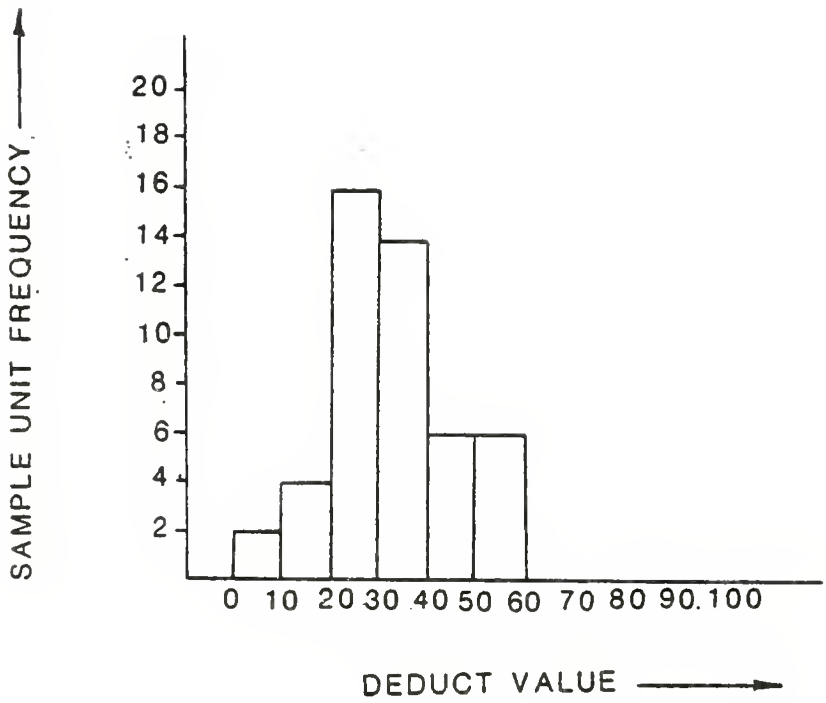


Figure 4.30 Deduct Value Distribution for Alligator Cracking.

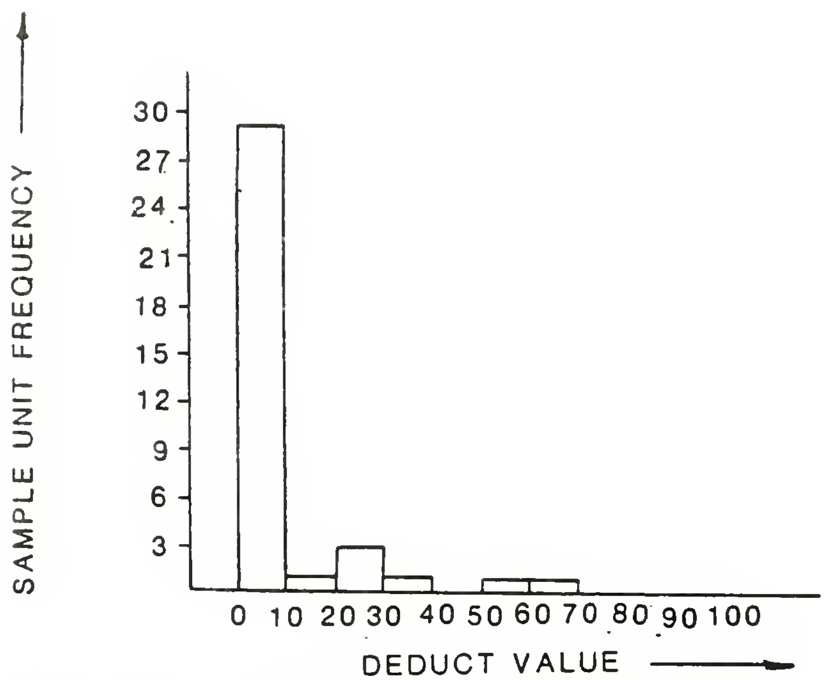


Figure 4.31 Deduct Value Distribuion for Bleeding.

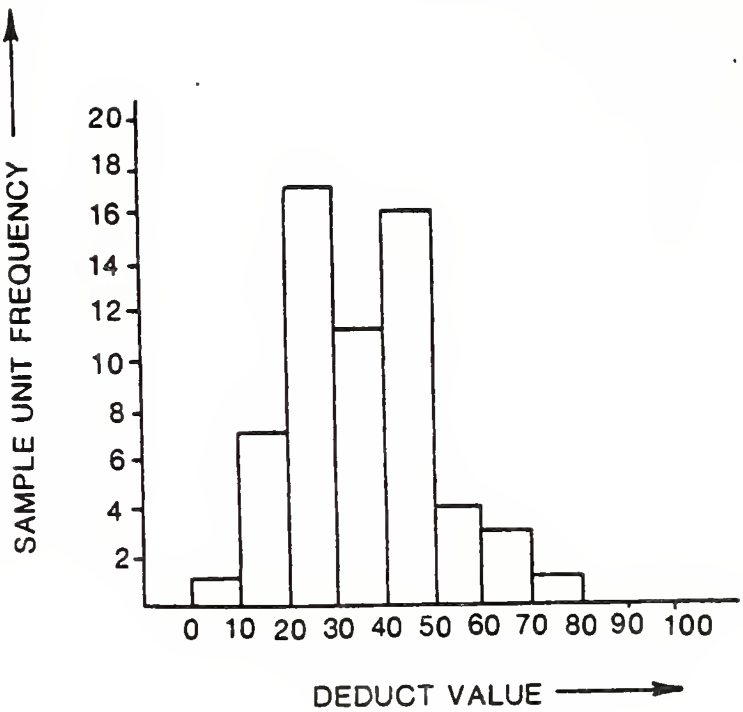


Figure 4.32 Deduct Value Distribution for Rutting.

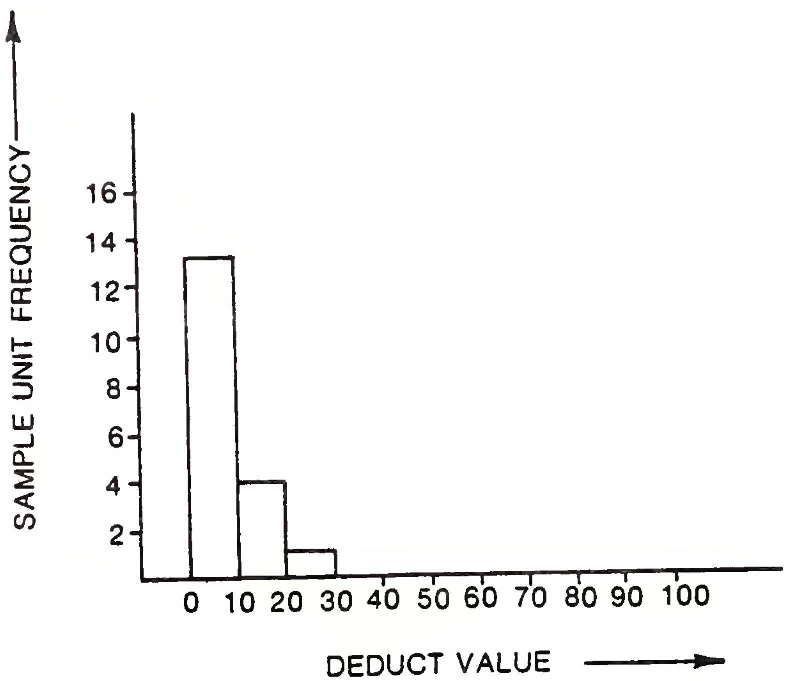


Figure 4.33 Deduct Value Distribution for Potholes.

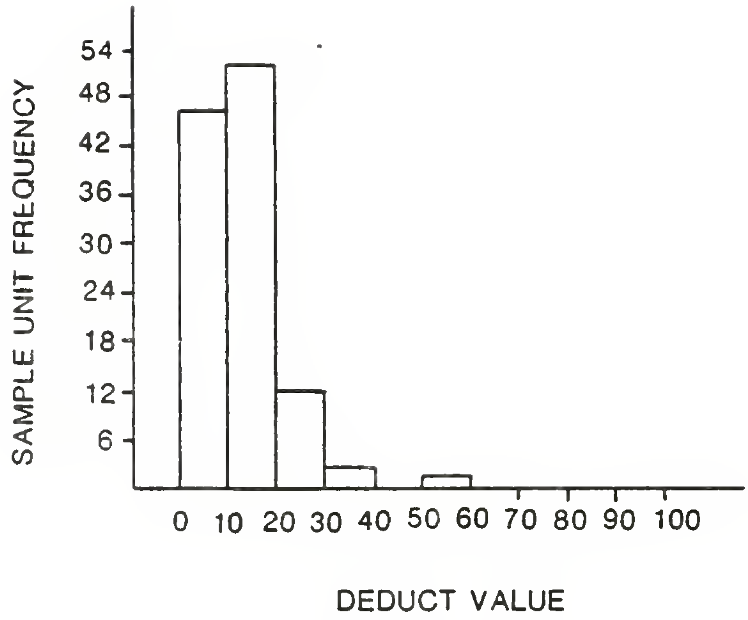


Figure 4.34 Deduct Value Distribution for Longitudinal and Transverse Cracks.

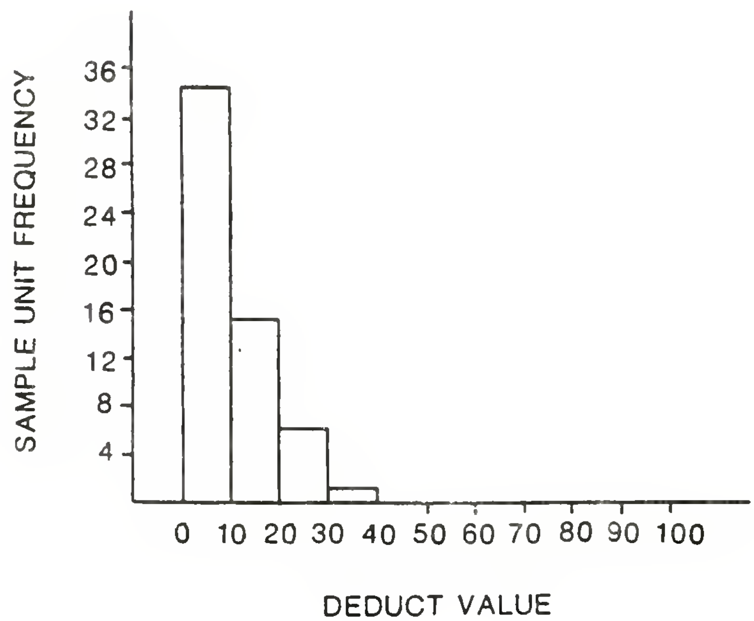


Figure 4.35 Deduct Value Distribution for Edge Cracking.

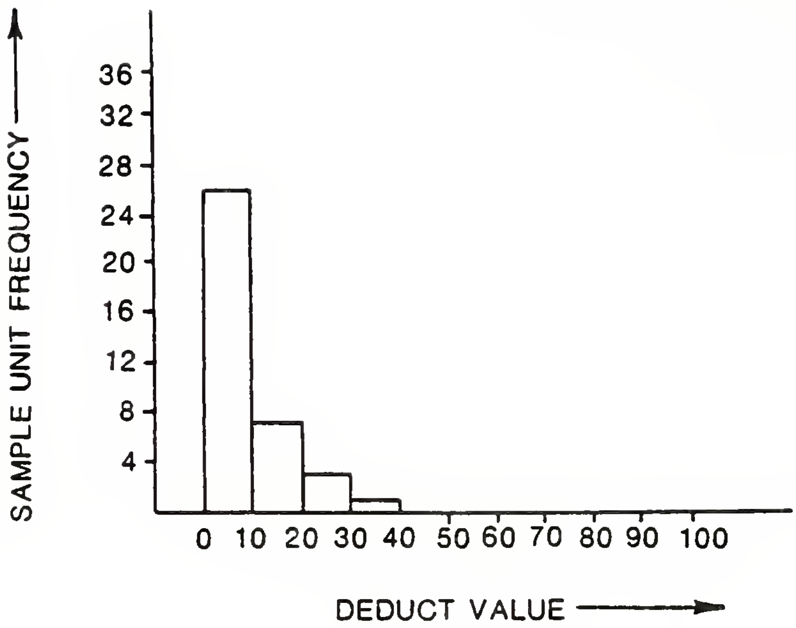


Figure 4.36 Deduct Value Distribution for Joint Reflection Cracking.

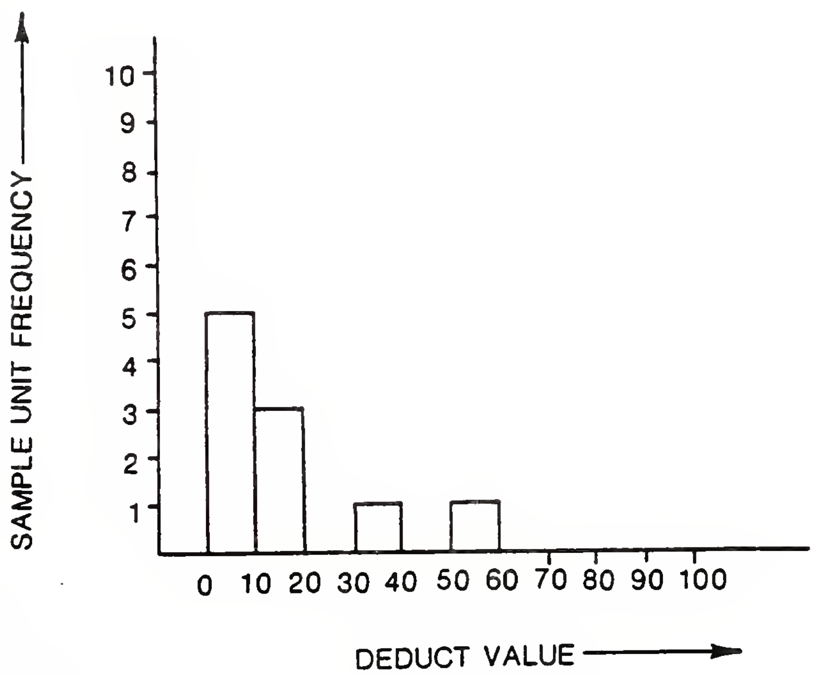


Figure 4.37 Deduct Value Distribution for Weathering and Raveling.

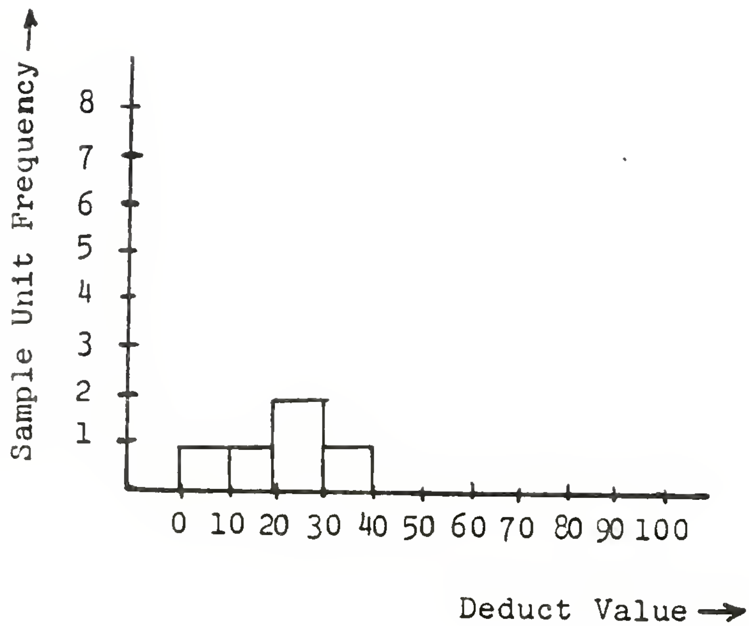


Figure 4.38 Deduct Value Distribution for Block Cracking.

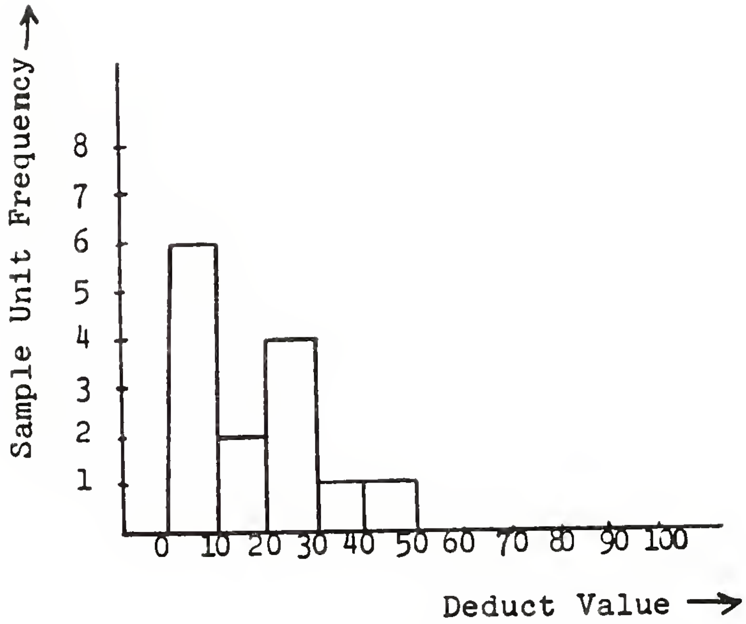


Figure 4.39 Deduct Value Distribution for Patching.

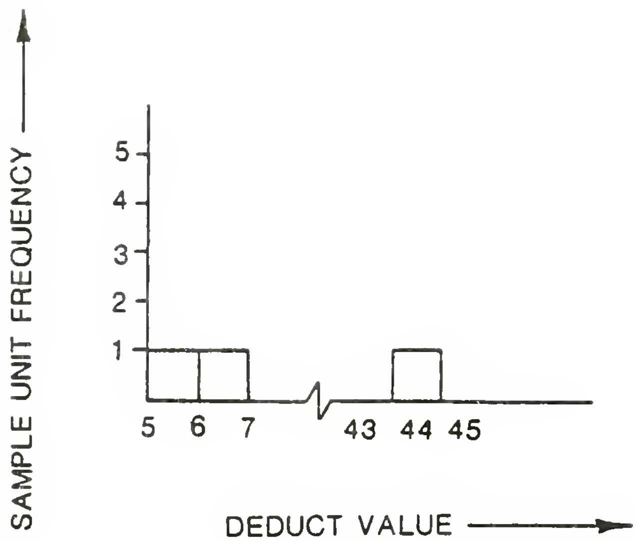


Figure 4.40 Deduct Value Distribution for Shoving.

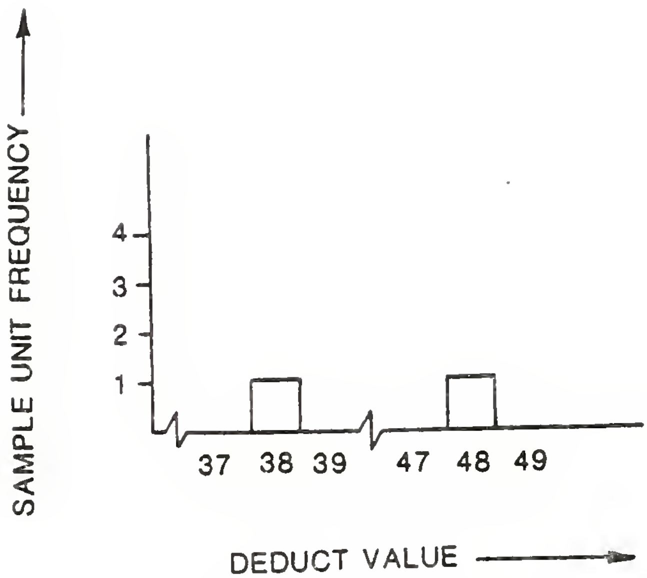


Figure 4.41 Deduct Value Distribution for Bumps and Sags.

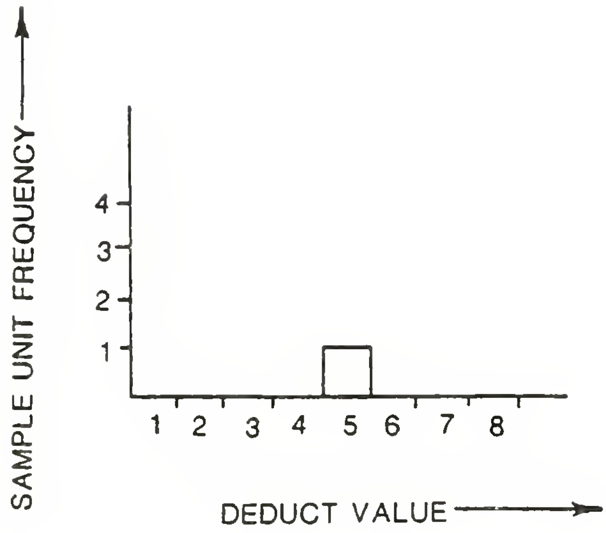


Figure 4.42 Deduct Value Distribution for Swelling.

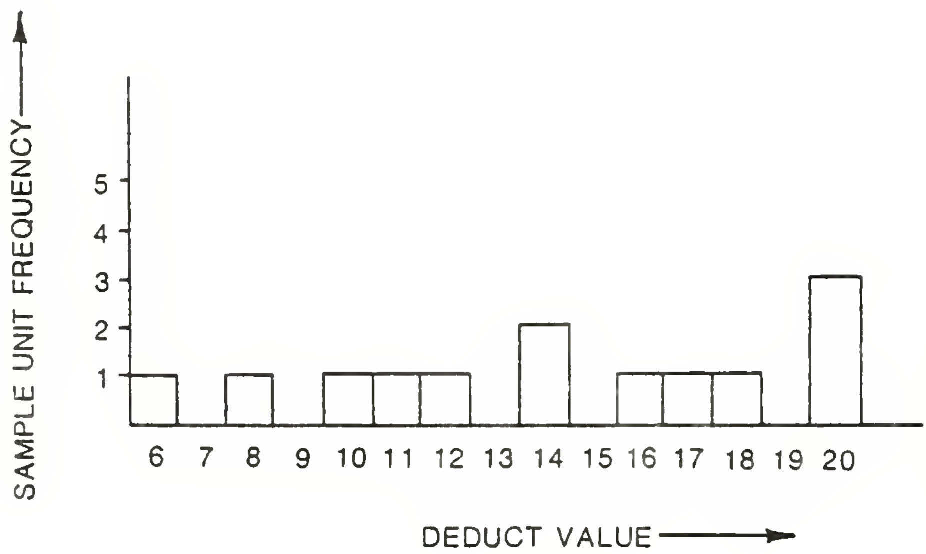


Figure 4.43 Deduct Value Distribution for Polished Aggregate.

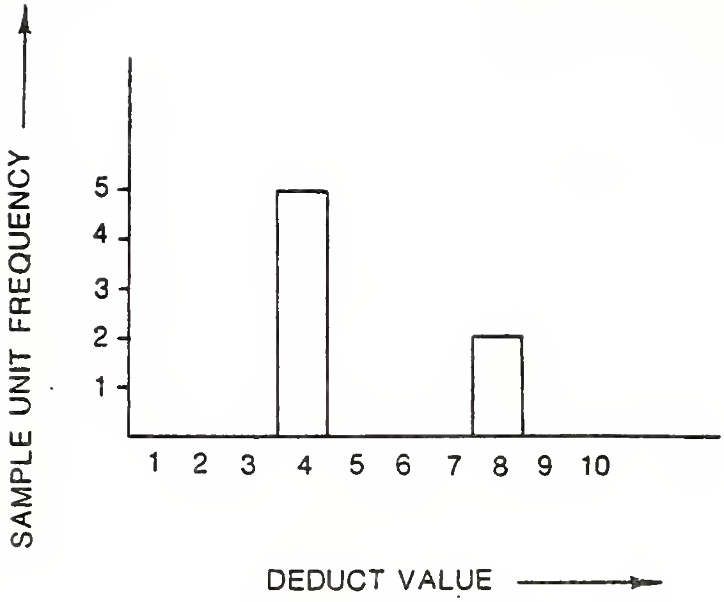


Figure 4.44 Deduct Value Distribution for Depressions.

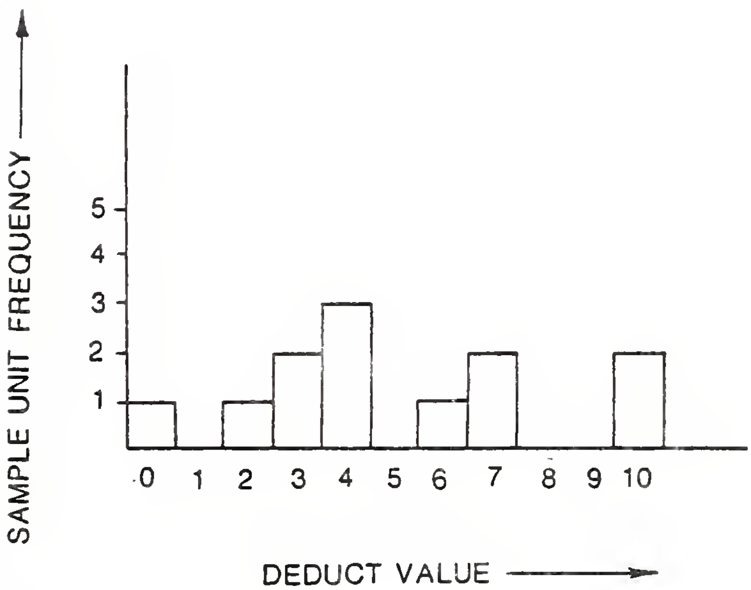


Figure 4.45 Deduct Value Distribution of Lane/Shoulder Drop-Off.

the ruts were classified as either medium or high severity, with almost 60 percent of the sections assigned a deduct value of at least 30 (see Figure 4.32).

4. Potholes were encountered on only 13 percent of the pavement sections. The deduct value was never greater than 30 (see Figure 4.33).

5. Longitudinal and transverse cracks are grouped into one major distress type, in contrast to the interstate condition survey. Over 83 percent of the pavement sections have this type of distress. Thirty-three percent of the longitudinal and transverse cracks were classified as either medium or high severity (see Figure 4.34).

6. Edge cracking was encountered on 51 percent of the sections of which 52 percent were classified as medium or high severity. The deduct value assigned to this distress was, in most cases, less than 30 (see Figure 4.35).

7. Joint reflection cracking was noticed on 35 percent of the pavement sections evaluated. Forty-six percent of the sections were considered to be of medium and high severity. Nevertheless, the deduct value assigned was, in most cases, between 0 and 20 (see Figure 4.36).

8. Weathering and raveling were present in only 7 percent of the pavement sections evaluated. On 20 percent of these sections the deduct value assigned was greater than 30 (see Figure 4.37).

9. Block cracking was present on only five of the pavement sections evaluated, but only one section was assigned a deduct value greater than 30 (see Figure 4.38).

10. Patches were encountered on fourteen of the pavement sections surveyed. Only two of the eight sections were assigned a defect rating of 30 or more (see Figure 4.39).

11. Shoving was present on only two pavement sections however, both sections were classified as medium severity and the deduct value assigned to them was always in excess of 30 (see Figure 4.40).

12. Bumps and sags were present in only three pavement sections, of which one was assigned a deduct value of 44 (see Figure 4.41).

13. The remaining distresses (swelling, polished aggregate, depression, and lane/shoulder drop-off) were not so critical in the pavement sections evaluated. The deduct value associated to these distresses was always below 20 (see Figures 4.42 through 4.45).

Concrete Pavements: Figure 4.46 shows the distribution of the pavement condition index for the concrete pavement sections evaluated in the Crawfordsville Highway District. Figure 4.47 shows the distribution of the concrete pavement distresses, while Figure 4.48 shows a further breakdown of these distresses according to severity level. Figures 4.49 through 4.57 show the deduct value distribution for each individual pavement distress. The most important aspects regarding these distributions are summarized below:

1. Durability cracks were encountered on 28 percent of the pavement sections evaluated and about 50 percent of them were classified as medium or high severity. However, only one of the sections was assigned a deduct value greater than 30 (see Figure 4.49).

2. The joint seal was damage in every concrete pavement section surveyed. Therefore, incompressible material is most likely to enter through the joints. However, the maximum deduct value assigned to this particular distress is only 8 (see Figure 4.50).

3. Spalled joints were encountered on over 90 percent of the pavement sections evaluated. Most of them, however, were classified as low severity (see Figure 4.51).

4. Popouts were encountered on 76 percent of the pavement sections but, the deduct value assigned to them was never greater than 20 (see Figure 4.52).

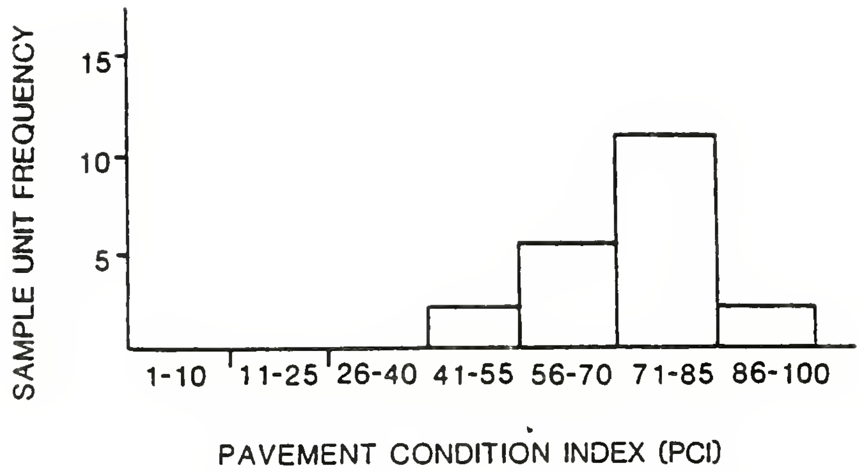


Figure 4.46 Distribution of the Pavement Condition Index (PCI) for Concrete Pavements Surveyed in the Crawfordsville Highway District.

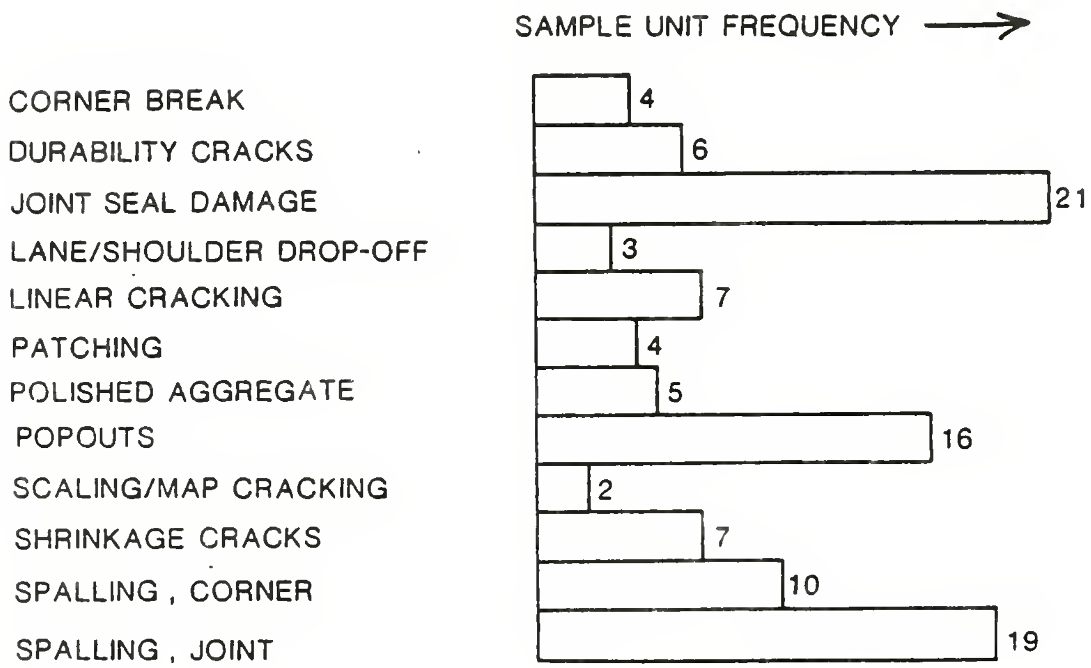


Figure 4.47 Distribution of Concrete Pavement Distresses in the Crawfordsville Highway District.

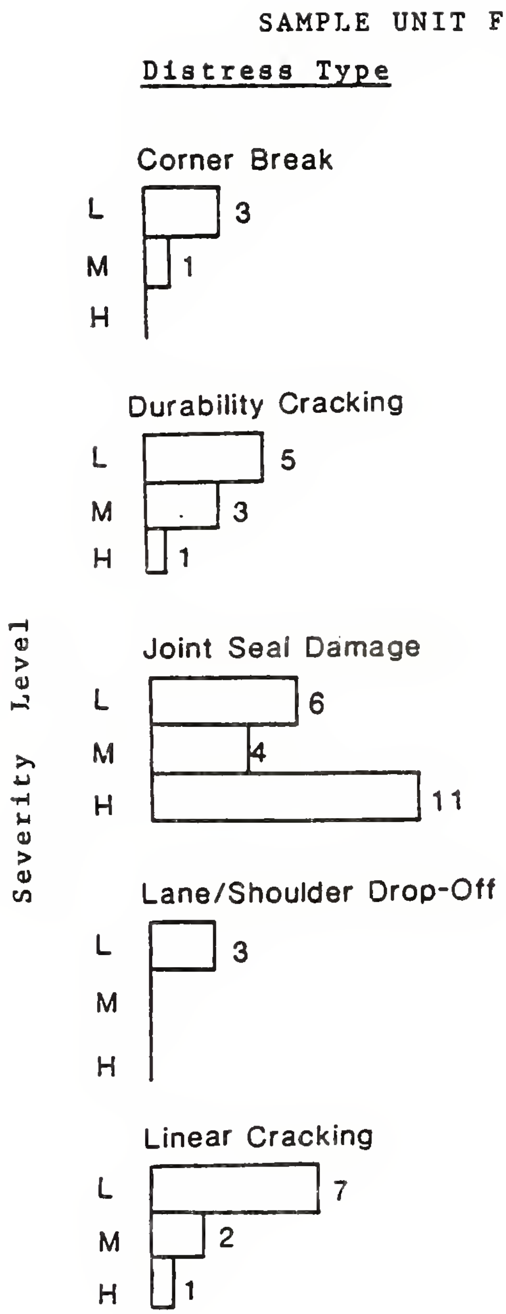


Figure 4.48 Distribution of Concrete Pavement Distresses in the Crawfordsville Highway District According to Severity Level.

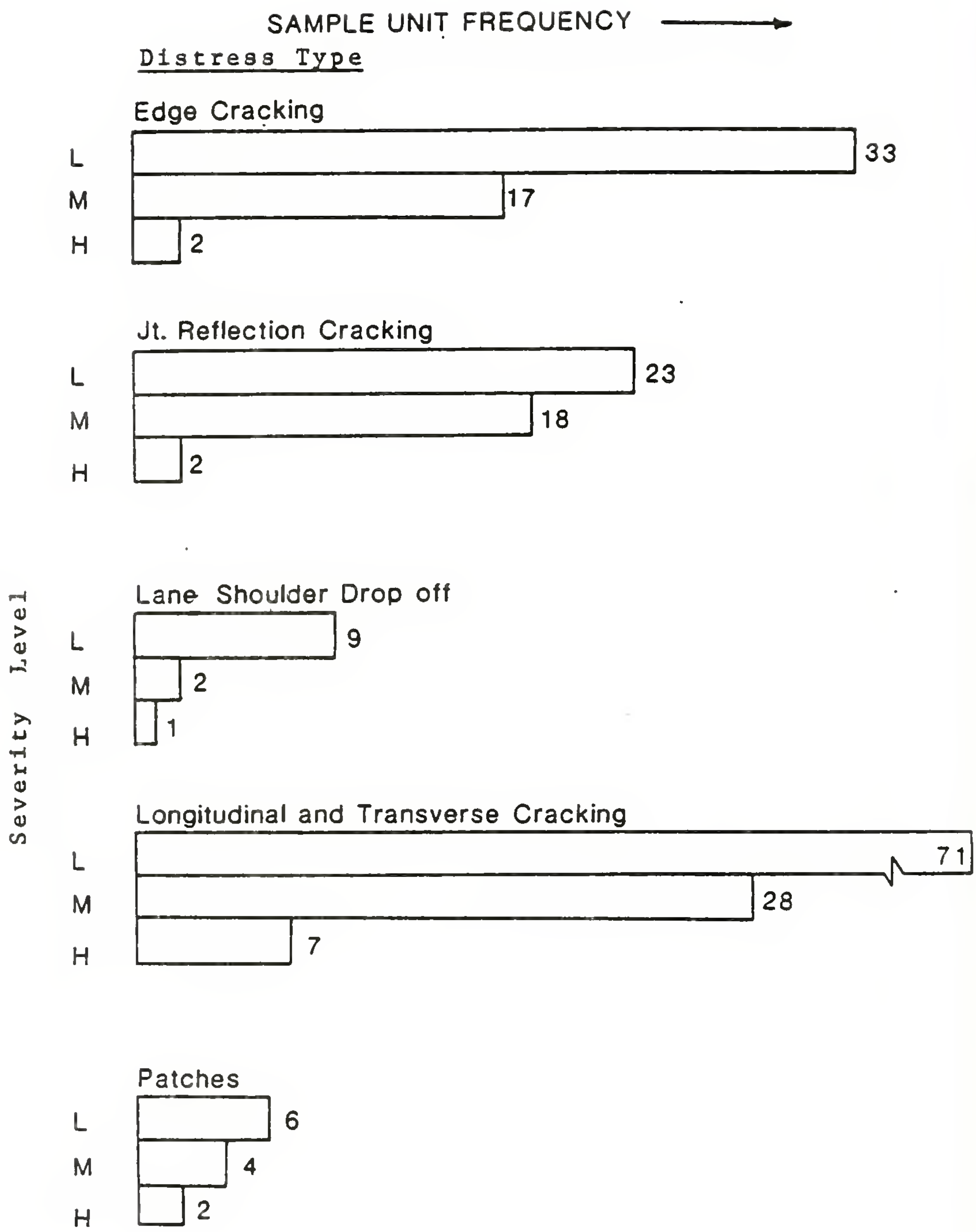


Figure 4.48 Distribution of Concrete Pavement Distresses in the Crawfordsville Highway District According to Severity Level (Continued).

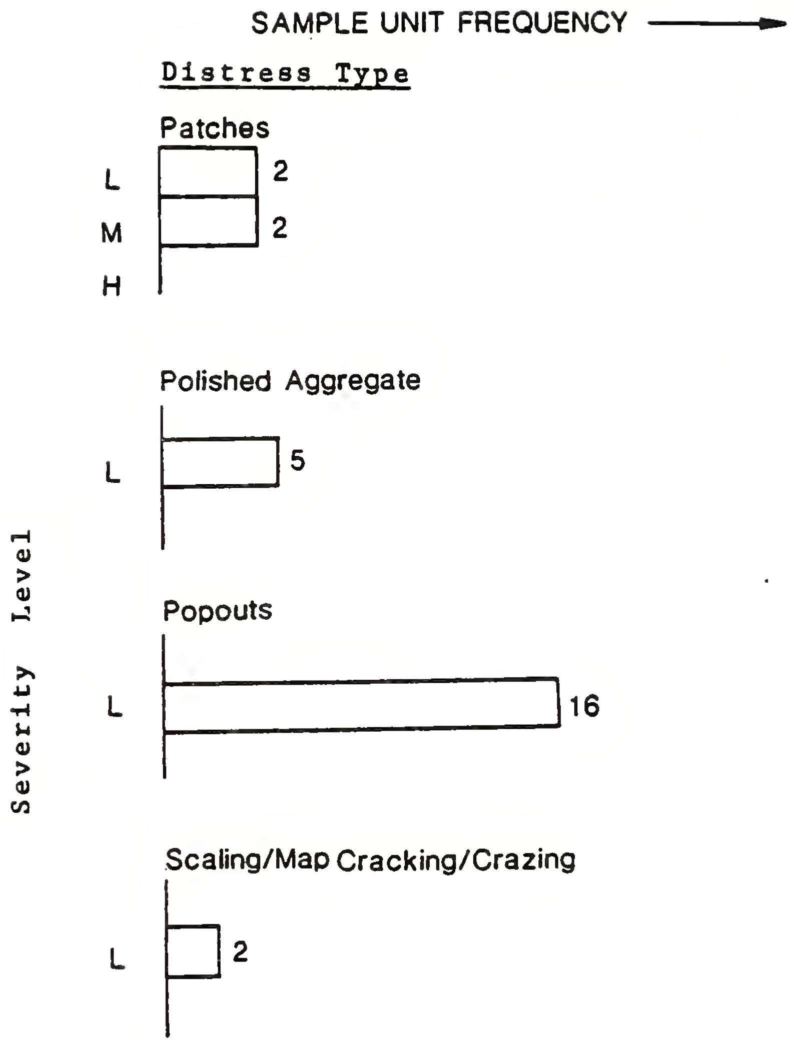


Figure 4.48 Distribution of Concrete Pavement Distresses in the Crawfordsville Highway District According to Severity Level (Continued).

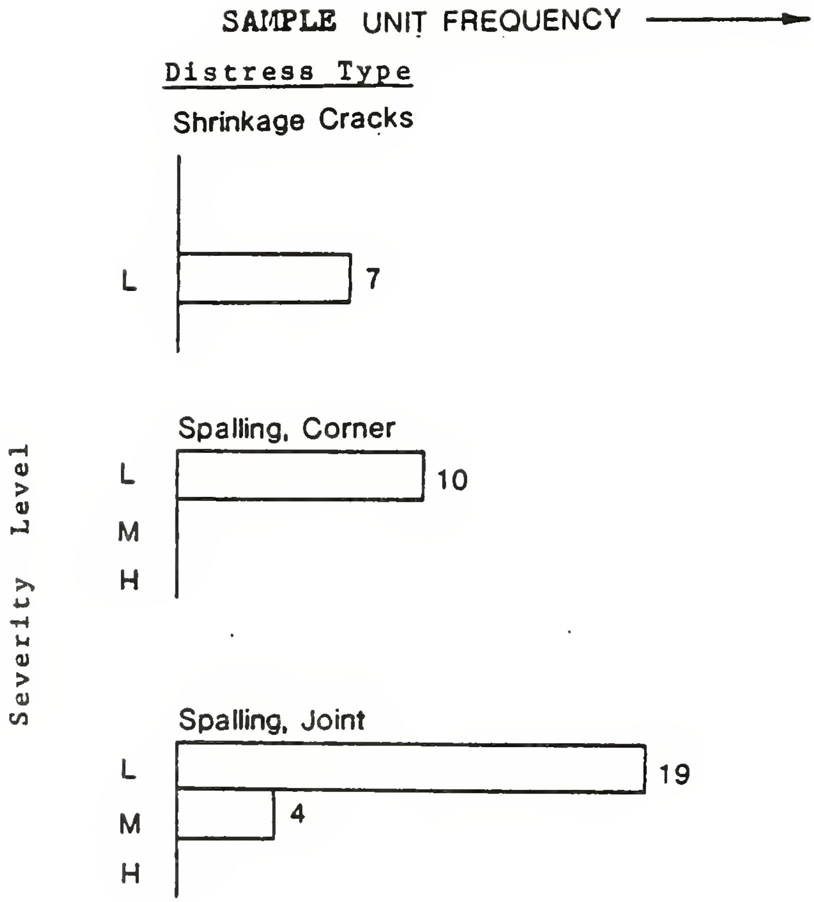


Figure 4.48 Distribution of Concrete Pavement Distresses in the Crawfordsville Highway District According to Severity Level (Continued).

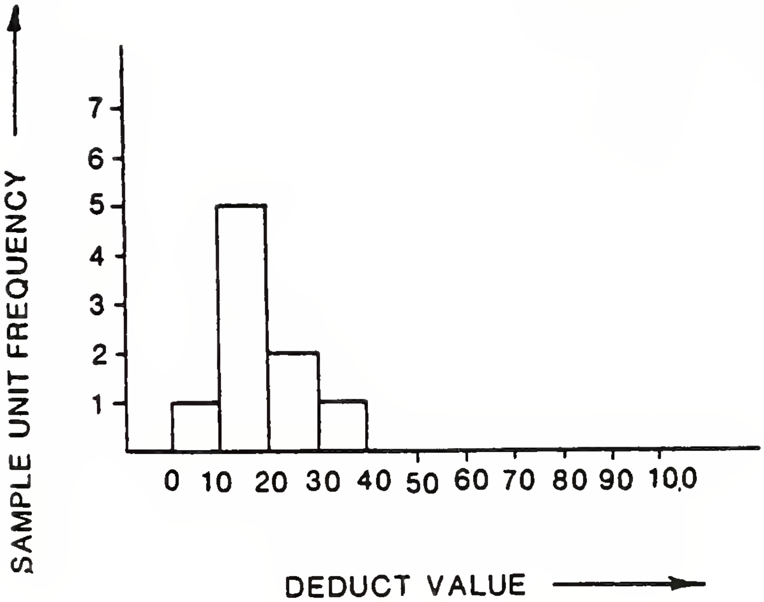


Figure 4.49 Deduct Value Distribution for Durability D-Cracks.

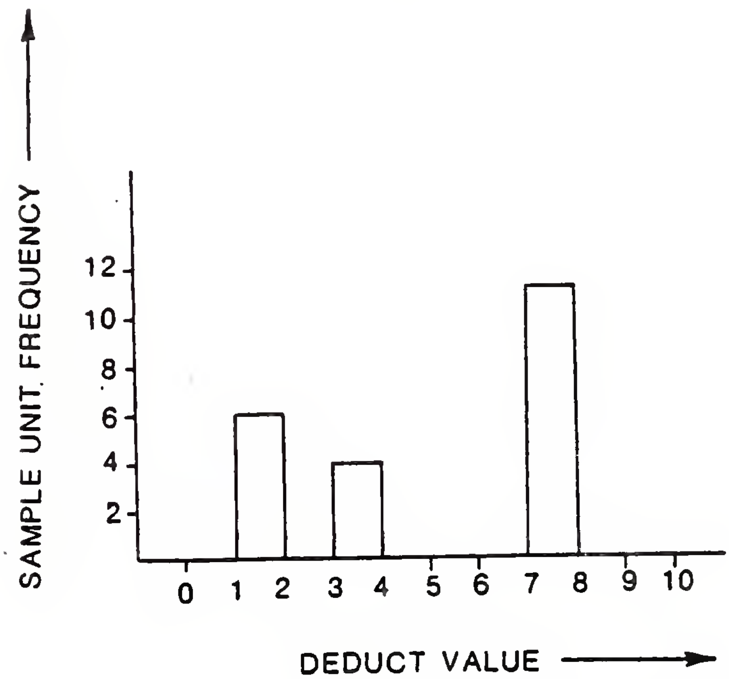


Figure 4.50 Deduct Value Distribution for Joint Seal Damage.

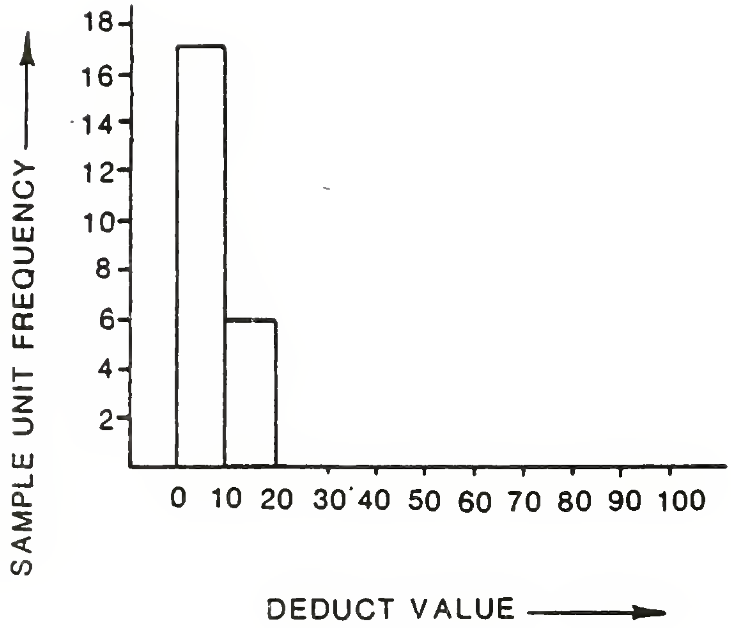


Figure 4.51 **Deduct Value Distribution for Joint Spalling.**

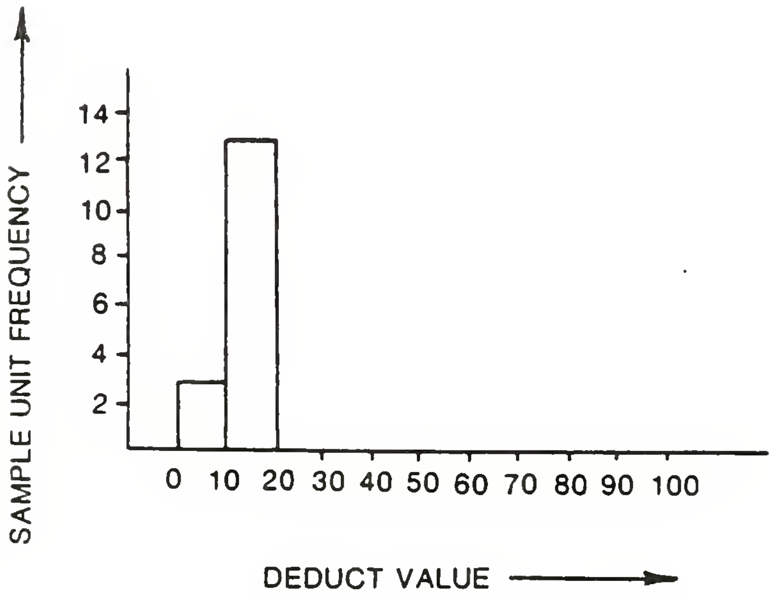


Figure 4.52 **Deduct Value Distribution for Popouts.**

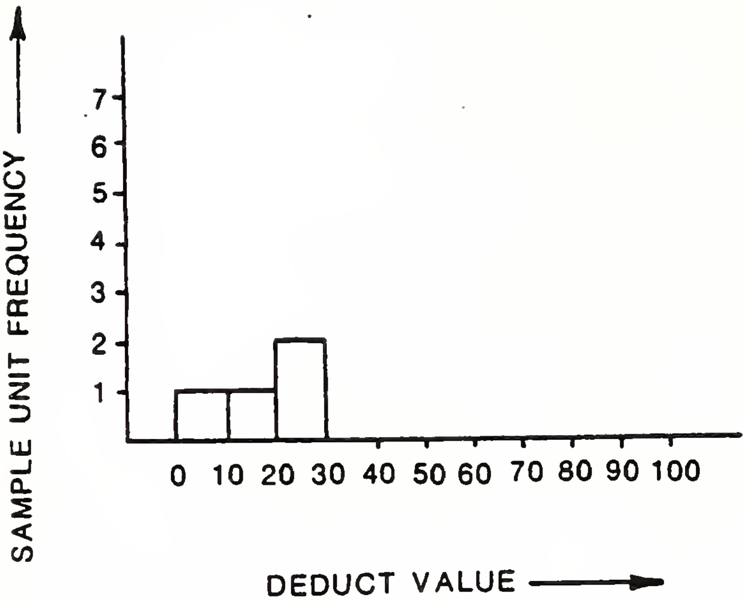


Figure 4.53 Deduct Value Distribution for Corner Break.

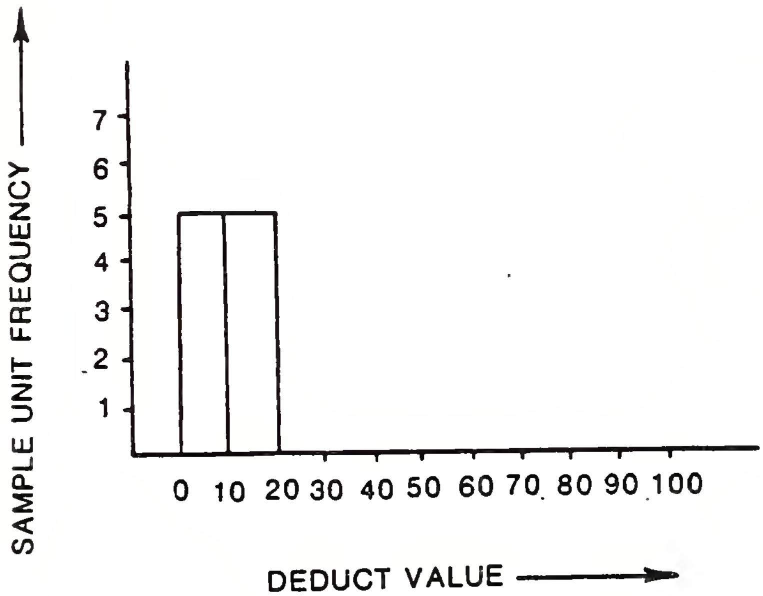


Figure 4.54 Deduct Value Distribution for Linear Cracking.

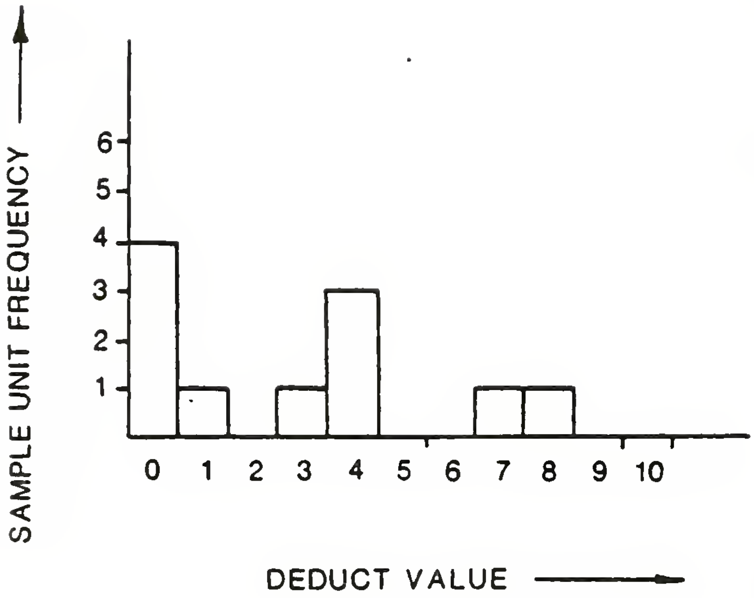


Figure 4.55 Deduct Value Distribution for Corner Spalling.

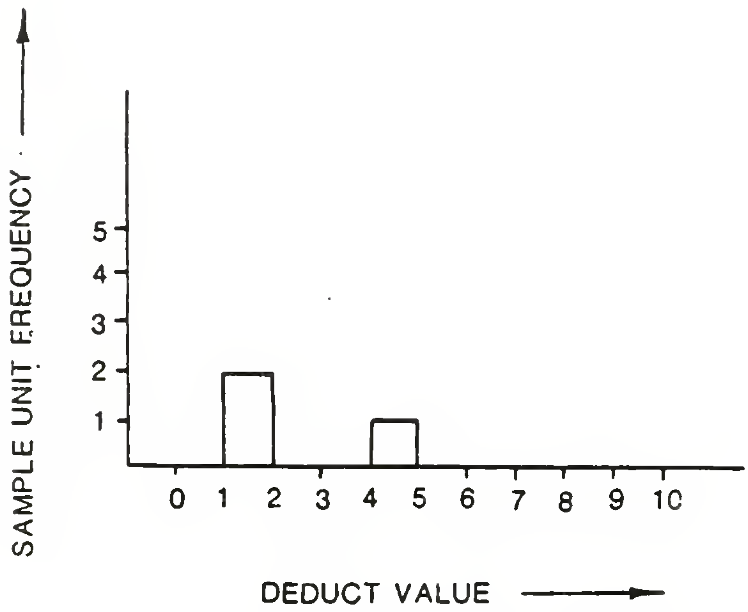


Figure 4.56 Deduct Value Distribution for Patching.

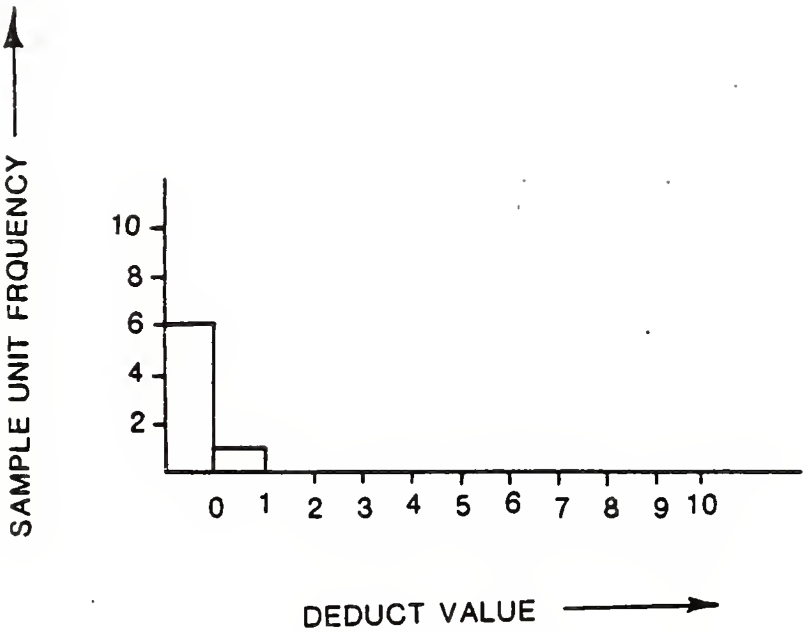


Figure 4.57 Deduct Value Distribution for Shrinkage Cracks.

5. Corner Break was present in only 19 percent of the pavement sections evaluated. The deduct value assigned never exceeded the value of 30 (see Figure 4.53).

6. Linear cracking, corner spalling, patching, and shrinkage cracks were also present but the deduct value assigned to them was always in the range of 0 to 20 (see Figures 4.54 through 4.57).

An attempt was also made to check whether or not a correlation existed between the roughness number, pavement condition index, pavement age, and traffic. As it was expected, there was little correlation between pavement condition index and roughness. In addition, the correlation between pavement condition index and current ADT was very low as well. Scatter plots of pavement condition index versus roughness and pavement condition index versus pavement age are presented in Figures 4.58 and 4.59. It can be seen that there is no specific pattern between pavement condition, roughness, and pavement age.

The primary reason for conducting the pavement condition survey was to have an objective measure of the pavement distresses observed on pavements throughout the state of Indiana. The importance of conducting a pavement condition survey has been recognized by highway agencies that have implemented pavement management systems at both the network and project level.

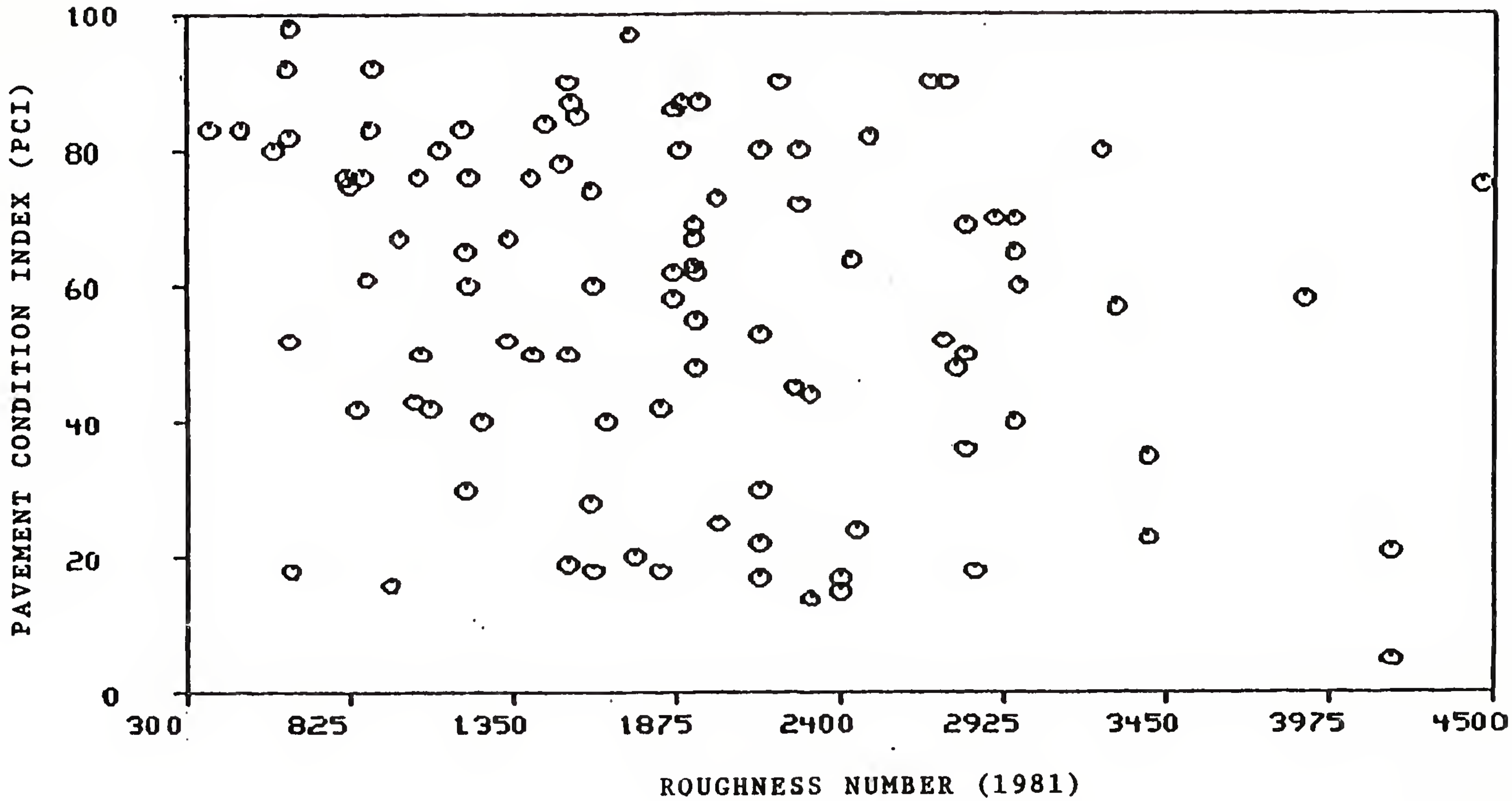


Figure 4.58 Relationship Between Pavement Condition Index and Roughness Number for Pavement Section Located in the Crawfordsville District.

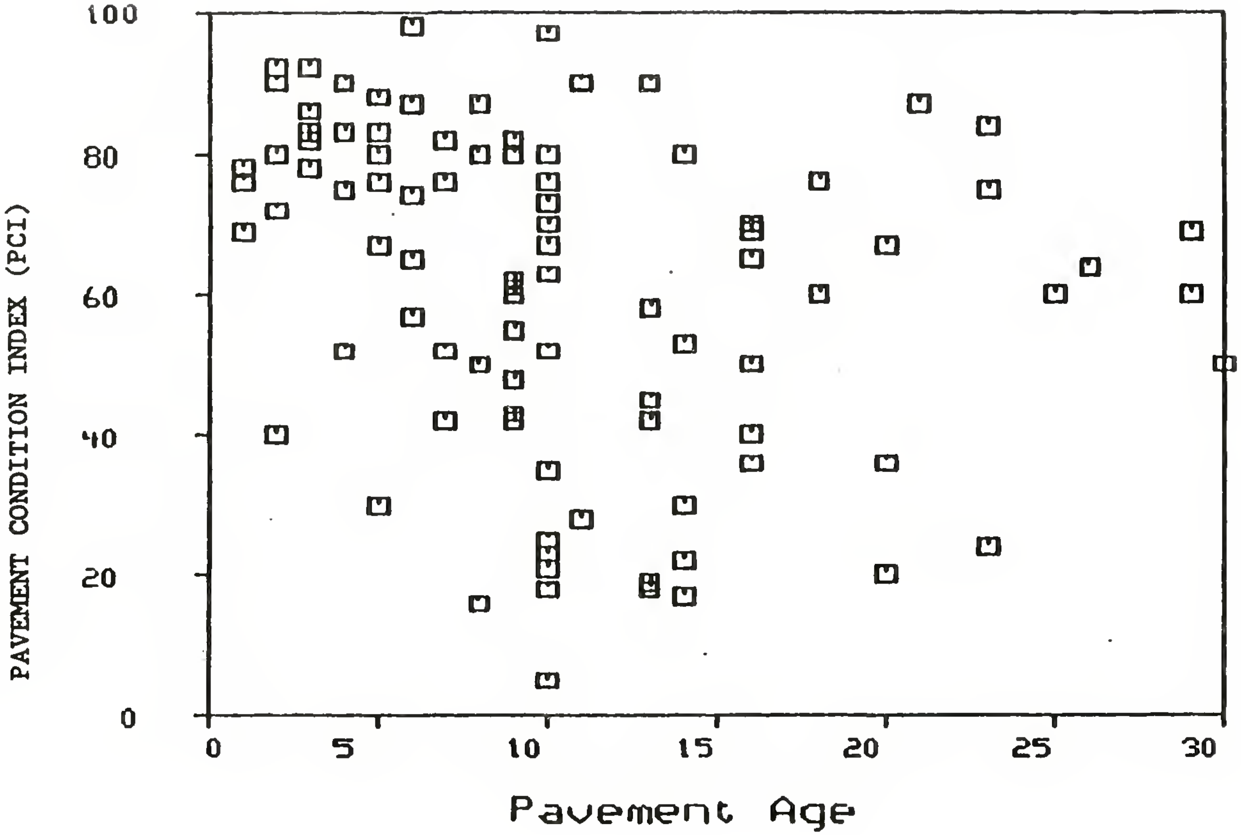


Figure 4.59 Relationship Between Pavement Condition Index and Pavement Age for Pavement Sections Located in the Crawfordsville District.

It should be kept in mind that the rating forms and rating manual used in this study to rate pavement sections in the Crawfordsville Highway District were developed initially for pavements located in military installations and not for pavements located in the Federal-aid primary and secondary system as used in this study. This method, however, was the best procedure available by the time of this survey.

Comparison of Rating Procedures

There are several differences between the two procedures used in this study to rate pavements in the Interstate system and the Federal-aid primary and secondary system. First, the PCI method uses an adjustment function which takes into account the different types of distresses present in a given pavement section, therefore it is not directly proportional to the magnitude and severity of the distresses encountered. For example, you might have a pavement section with just ruts along the wheelpath and no other major distress and the section will be assigned a pavement condition index of about 55. On the other hand, if the rating procedure developed by IDOH is used, the maximum deduction for the same type of distress is just 10 points, therefore, the pavement condition rating assigned to the same pavement section will be 90 instead of 55.

Another major difference is the fact that the IDOH rating form takes into account the overall riding quality of the pavement section in question in the final rating. The amount deducted from the final rating is a function of the roughness number, for example, if the roughness number of a concrete pavement section is between 2000 and 2250, between 0 and 3 points are deducted from the overall rating. If the roughness number is between 2251 and 2570, between 4 and 7 points are subtracted, up to a roughness number of 3800, in which a maximum of 10 points are deducted.

The PCI method does not take into account the riding quality in terms of the roughness number, however, is considered in a rather subjective manner. The final rating however is not greatly affected as it is the case when the IDOH rating procedure is used. This is the main reason why a correlation was encountered when using the IDOH rating forms between pavement condition rating and roughness. Since roughness is already taken into account in the process of computing the pavement condition rating, it is most likely that pavements which show higher levels of roughness have, in a sense, a lower rating. In statistics, the variable roughness is often referred as a concomitant variable [99].

Summary

This chapter described the two pavement condition surveys which were conducted to provide an objective measure of the pavement distresses currently encountered in Indiana. Different methods were used to rate pavements in the Interstate system and in the Federal-aid primary and secondary systems. The significant statistics pertaining to these two surveys were presented in this chapter.

In summary, it can be inferred that the pavement condition index or pavement condition rating provides an additional information pertaining to the pavement structure which the PCA roadmeter cannot detect. It was shown that no correlation existed between PCI and roughness measurements for pavement sections in the Crawfordsville Highway District. On the other hand, correlations were observed in the Interstate system and regression models showing pavement condition index as a function of roughness, pavement age, and traffic were developed. These correlations, however, are in part due to the nature of the rating procedure used. Furthermore, both methods are quite different in the manner they compute the overall rating for the pavement section in question.

It was not the intent of this research project to conduct an extensive evaluation of pavements in-situ, but to

show the importance of an objective measurement of pavement surface condition as part of the pavement management program envisioned by the state.

The approach used in this study to combine pavement condition data, roughness data, traffic, and age of the pavement into an overall index to be used in the optimization model is described in the following chapter.

CHAPTER 5

DEVELOPMENT OF PERFORMANCE FUNCTION AND ANALYSIS OF ROUGHNESS NUMBER CHARACTERISTICS

Introduction

This chapter is divided into two parts. The first part describes the methodology used in this study for developing a performance function model. The second part summarizes the different types of analysis performed with roughness data including an analysis of roughness number stochastic characteristics.

Development of Performance Function

Purpose

Performance functions provide a measure of the overall improvement of a particular pavement section that can be achieved after the application of a given resurfacing strategy. The overall improvement of a pavement section can be expressed, for example, in terms of total reduction in roughness. This improvement can also be expressed in terms of change in pavement condition index or change in pavement friction or any other factor the state highway department decides to use as a measure of effectiveness of resurfacing strategies at the network level.

In order to use the optimization program, it is essential that a quantitative procedure is available to assess the level of improvement in pavement condition that can be expected from each of the feasible resurfacing strategies. In general, it can be expected that as the cost of the resurfacing strategy increases, the overall improvement of the pavement section is also expected to increase in the long run.

Data Collection

The procedure used to develop the performance function is shown in Figure 5.1. The data used were essentially the roughness number of the pavement section prior to resurfacing, roughness number after resurfacing, and the type of resurfacing strategy performed on the pavement section in question. In order to perform this task, the following guidelines were followed:

1. All contract sections selected for this task should have roughness measurements made within 6 months prior to resurfacing and no later than 6 months after it has been resurfaced. This criterion was established since our primary interest is the immediate improvement accomplished by the resurfacing strategy in question and not after the section has been exposed to considerable amount of traffic and weather.

2. All new resurfaced pavement sections should correspond to the same fiscal year so that the cost estimates associated with each resurfacing strategy are for the same year. This way the effect of inflation upon resurfacing costs can be neglected.

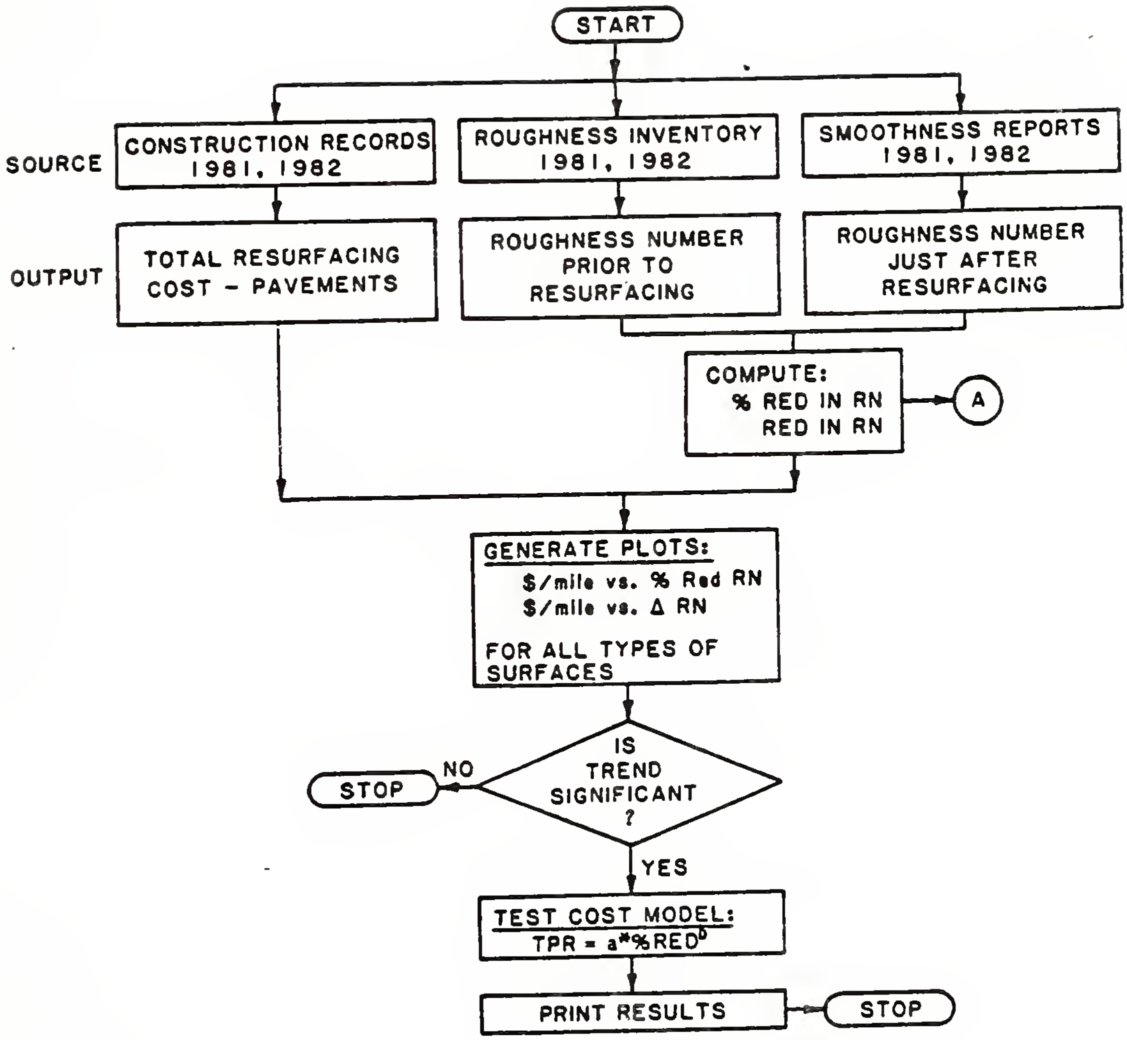


Figure 5.1 Flowchart Describing Methodology Used in the Development of the Performance Function Model.

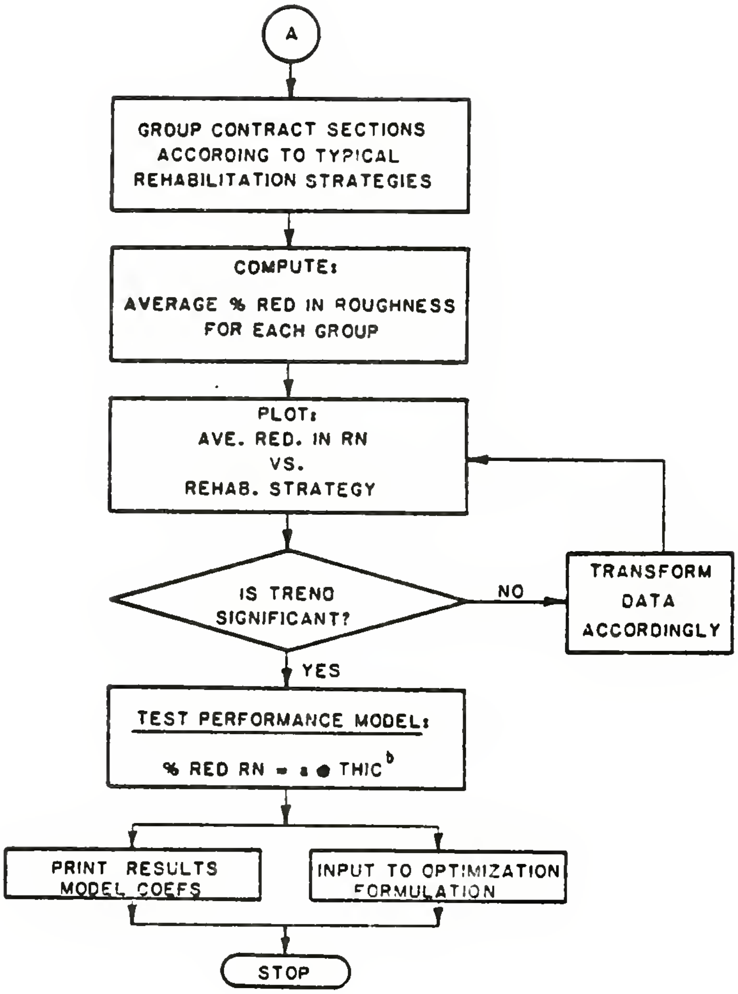


Figure 5.1 Flowchart Describing Methodology Used in the Development of the Performance Function Model (Continued).

3. The cost figures extracted from the construction forms should only be associated with the cost of the pavement structure.

The final construction records related to the paving resurfacing contracts performed during fiscal years 1981 and 1982 were used to estimate the total resurfacing costs associated with each of the resurfacing activities performed during this period. The roughness number for each contract section prior to resurfacing was obtained from the roughness inventory published by the Research and Training Center. The roughness number just after resurfacing was extracted from the smoothness reports prepared by the Research and Training Center every year for the smoothness award. The smoothness reports list, in ascending order, the roughness number of all resurfacing contracts performed during fiscal year in question. The resurfacing contracts considered were performed on Interstate as well as on Federal-aid primary and secondary roads. A total of 56 resurfacing contracts were undertaken during 1981 and 62 contracts during 1982. The corresponding miles were 402 and 538, respectively.

Data Analysis

The percent reduction in roughness was calculated for each pavement contract section resurfaced during fiscal year 1982 that met the guidelines previously discussed.

The equation used to calculate percent reduction in roughness is as follows:

$$RN_r = \frac{(RN_b - RN_a)}{RN_b} * 100 \qquad (5.1)$$

where:

RN_r = percent reduction in roughness number after contract section has been resurfaced;

RN_b = roughness number prior to resurfacing;

RN_a = roughness number after resurfacing.

The percent reduction in roughness number and the change in roughness number were then plotted against the cost per mile associated with each pavement section in order to check whether or not there was any significant trend. It is important to note that these plots were generated using all contract sections irrespective of the type of surface (i.e. Hot Asphaltic Emulsion (HAE), Hot Asphalt Concrete (HAC), Modified HAC, and so on). The results of these plots are shown in Figures 5.2 and 5.3.

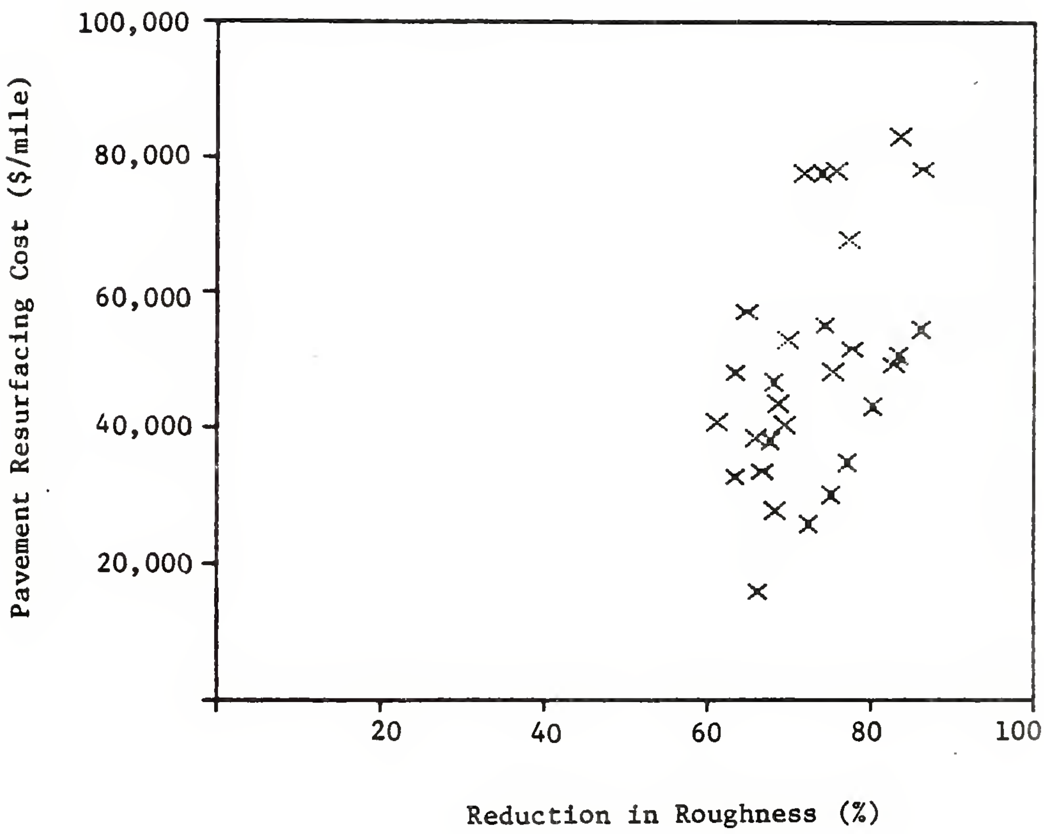


Figure 5.2 Relationship Between Pavement Resurfacing Cost and Percent Reduction in Roughness for Pavement Sections Resurfaced During 1982.

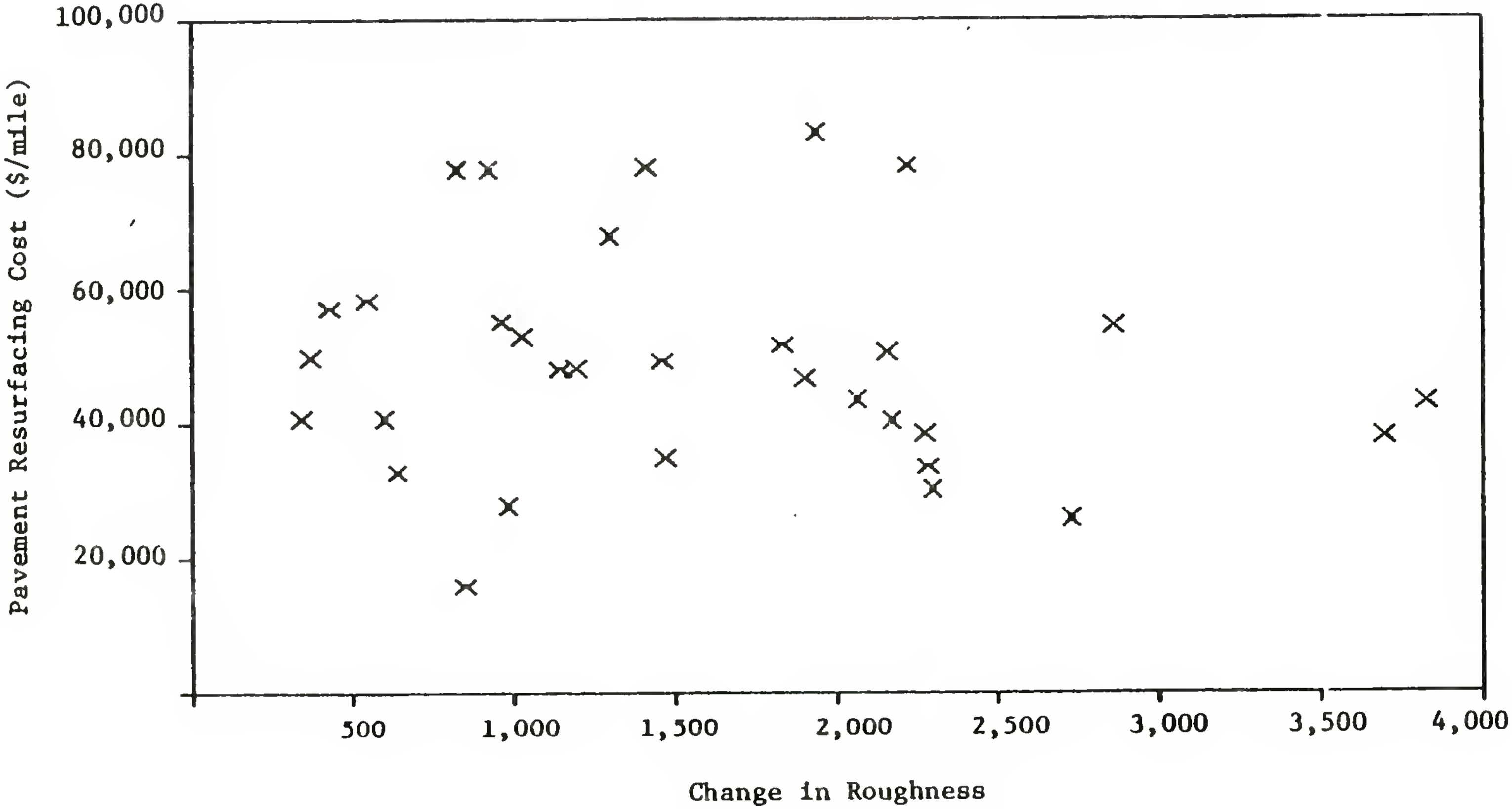


Figure 5.3 Relationship Between Pavement Resurfacing Cost and Change in Roughness for Pavement Sections Resurfaced During 1982.

Based on these plots the following observations can be made:

1. Although there was no significant statistical relationship, an overall increasing trend in pavement resurfacing cost could be noted with increasing percent reduction in roughness (see Figure 5.2).

2. No significant statistical relationship could be observed between pavement resurfacing cost and change in roughness number for pavement sections resurfaced in 1982 (see Figure 5.3).

At this stage it was decided to generate individual plots for each type of surface to check whether a stronger relationship could be established. Plots were generated for only those types of surface for which at least four observations were available. These are:

1. Hot Asphalt Emulsion Type II
2. Hot Asphalt Emulsion Type III
3. Hot Asphalt Emulsion Type IV
4. Hot Asphaltic Concrete Type A

These plots are shown in Figures 5.4 through 5.11. The primary observations from these plots are summarized below:

1. In general, all four types of surfaces showed an increasing trend between percent reduction in roughness number and pavement resurfacing cost (Figures 5.4 through 5.7).

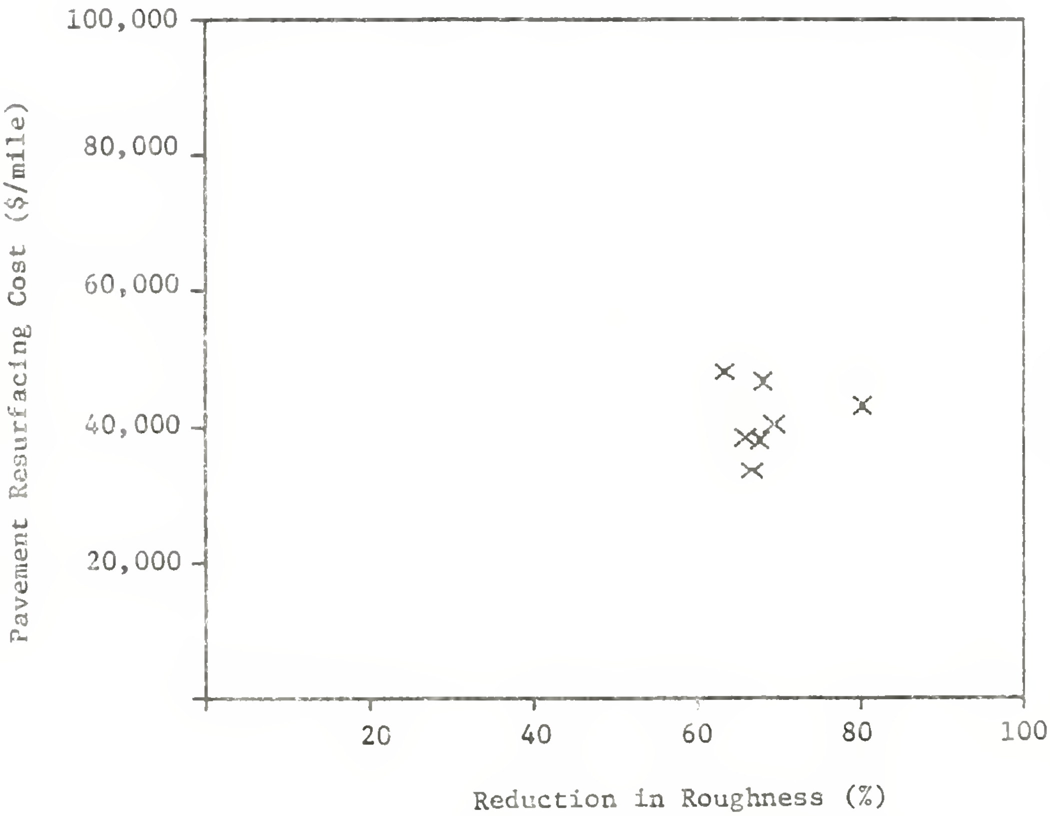


Figure 5.4 Relationship Between Pavement Resurfacing Cost and Percent Reduction in Roughness for Pavements Resurfaced with HAE Type II During 1982.

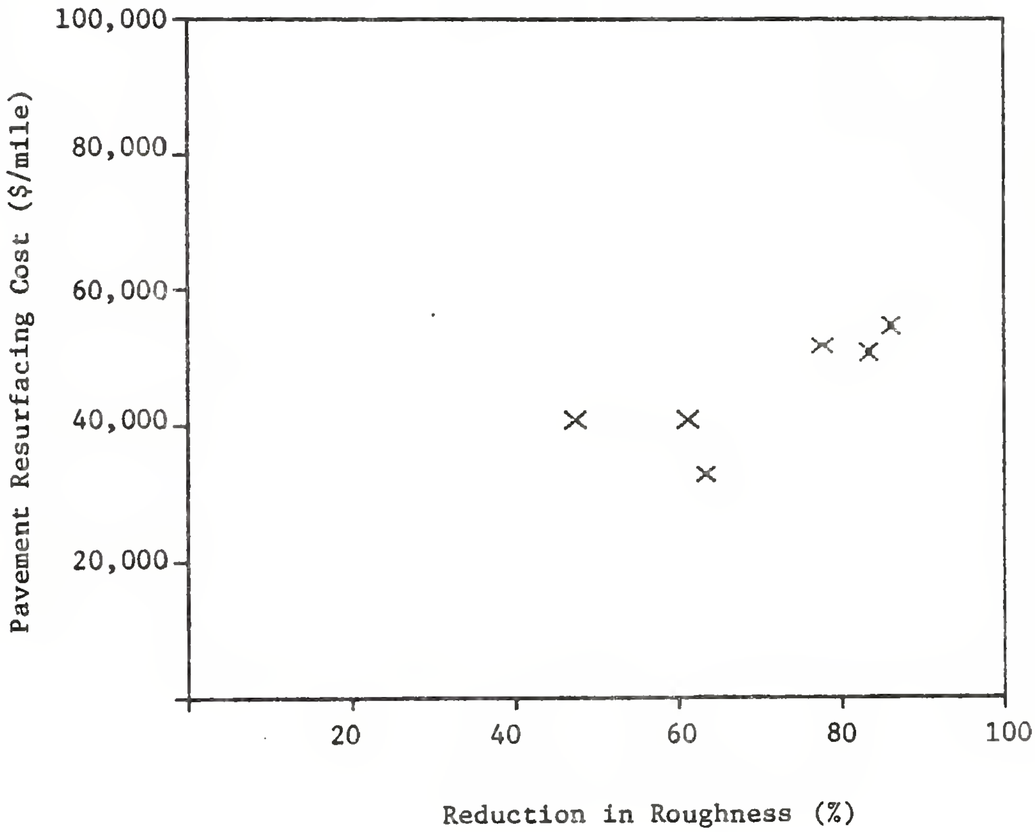


Figure 5.5 Relationship Between Pavement Resurfacing Cost and Percent Reduction in Roughness for Pavements Resurfaced with HAE Type III During 1982.

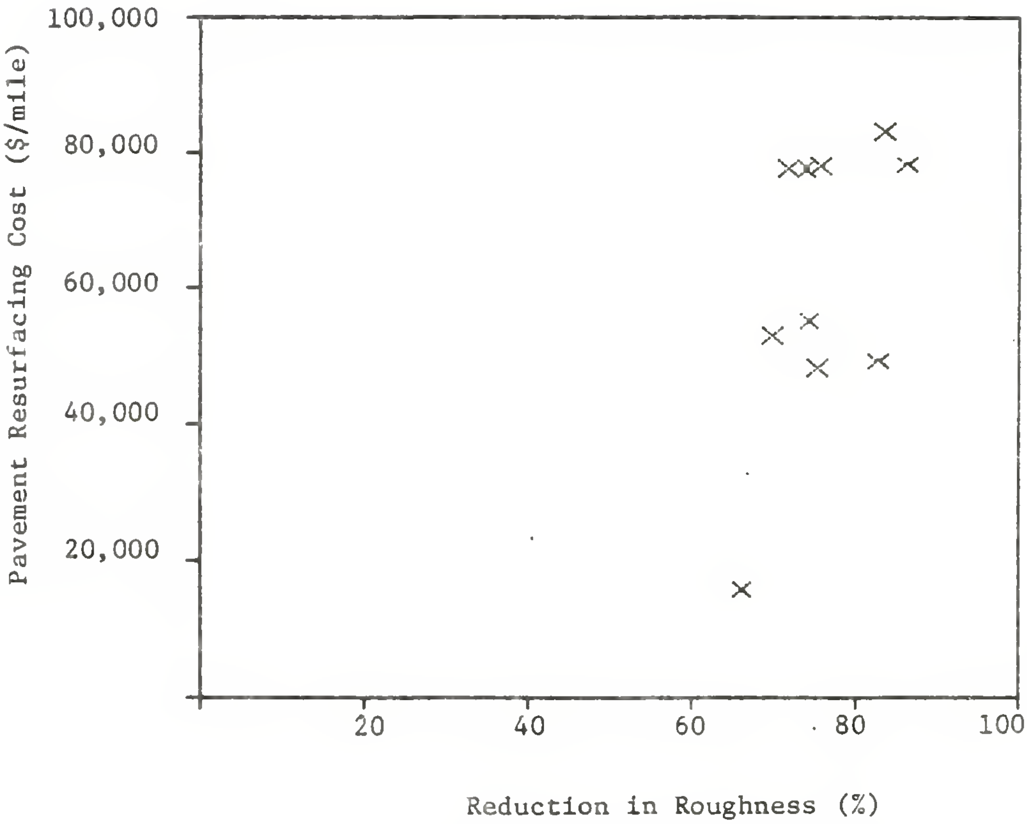


Figure 5.6 Relationship Between Pavement Resurfacing Cost and Percent Reduction in Roughness for Pavements Resurfaced with HAE Type IV During 1982.

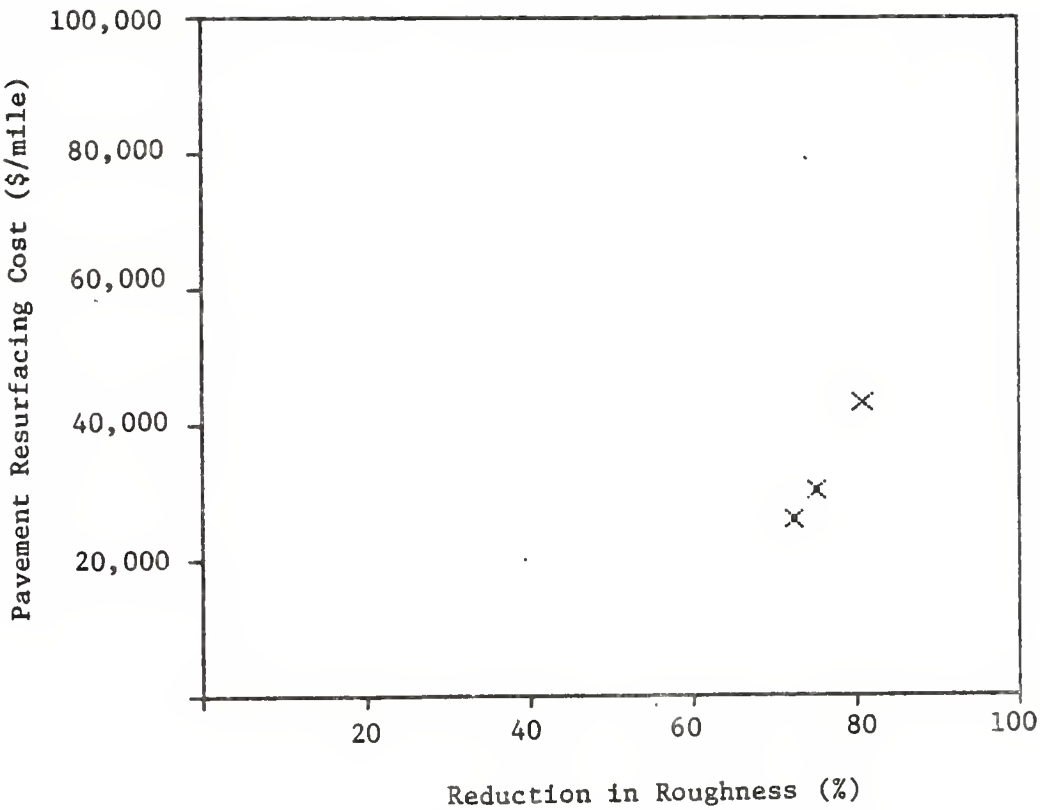


Figure 5.7 Relationship Between Pavement Resurfacing Cost and Percent Reduction in Roughness for Pavements Resurfaced with HAC Type A During 1982.

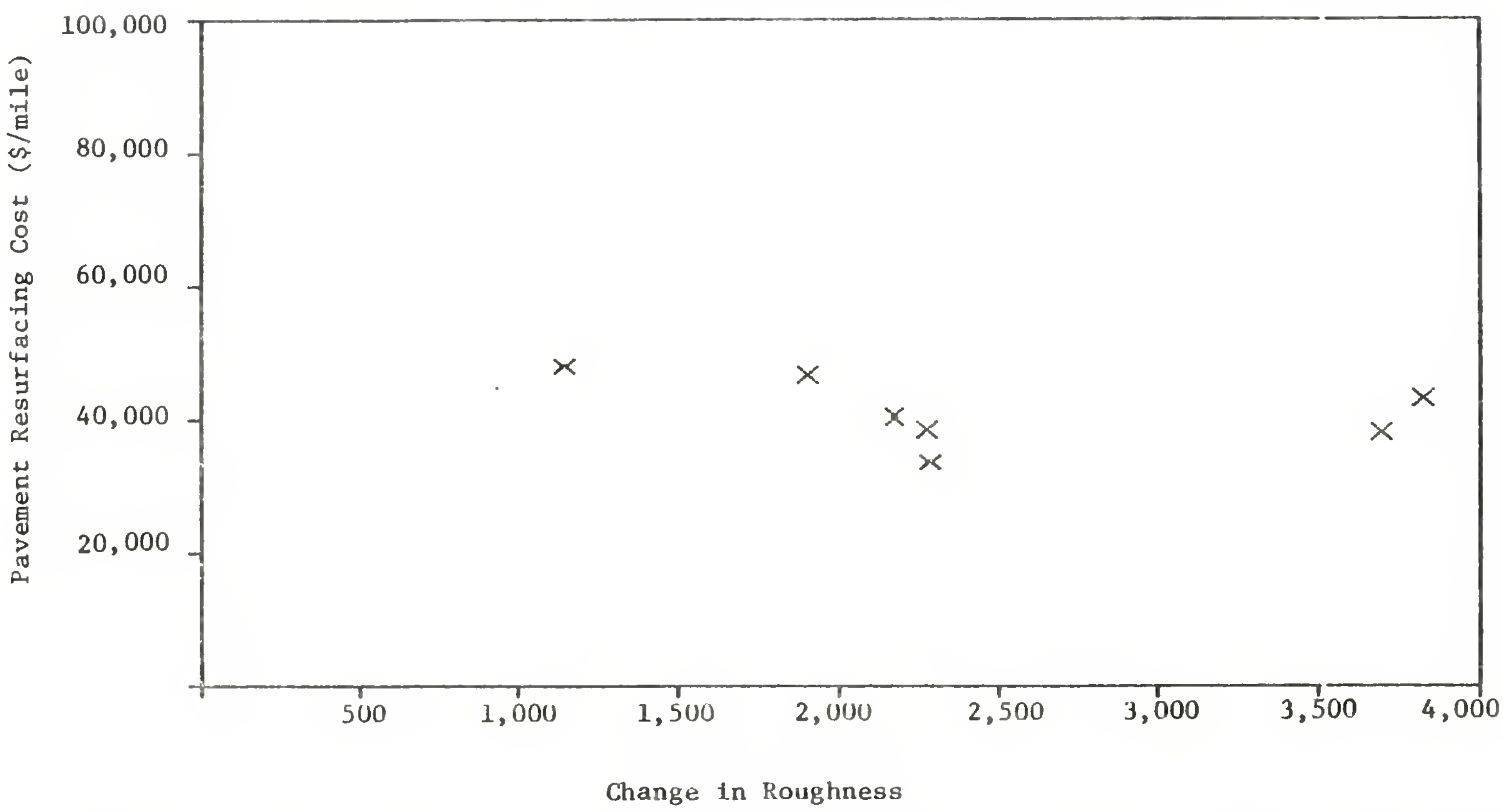


Figure 5.8 Relationship Between Pavement Resurfacing Cost and Change in Roughness for Pavements Resurfaced with HAE Type II During 1982.

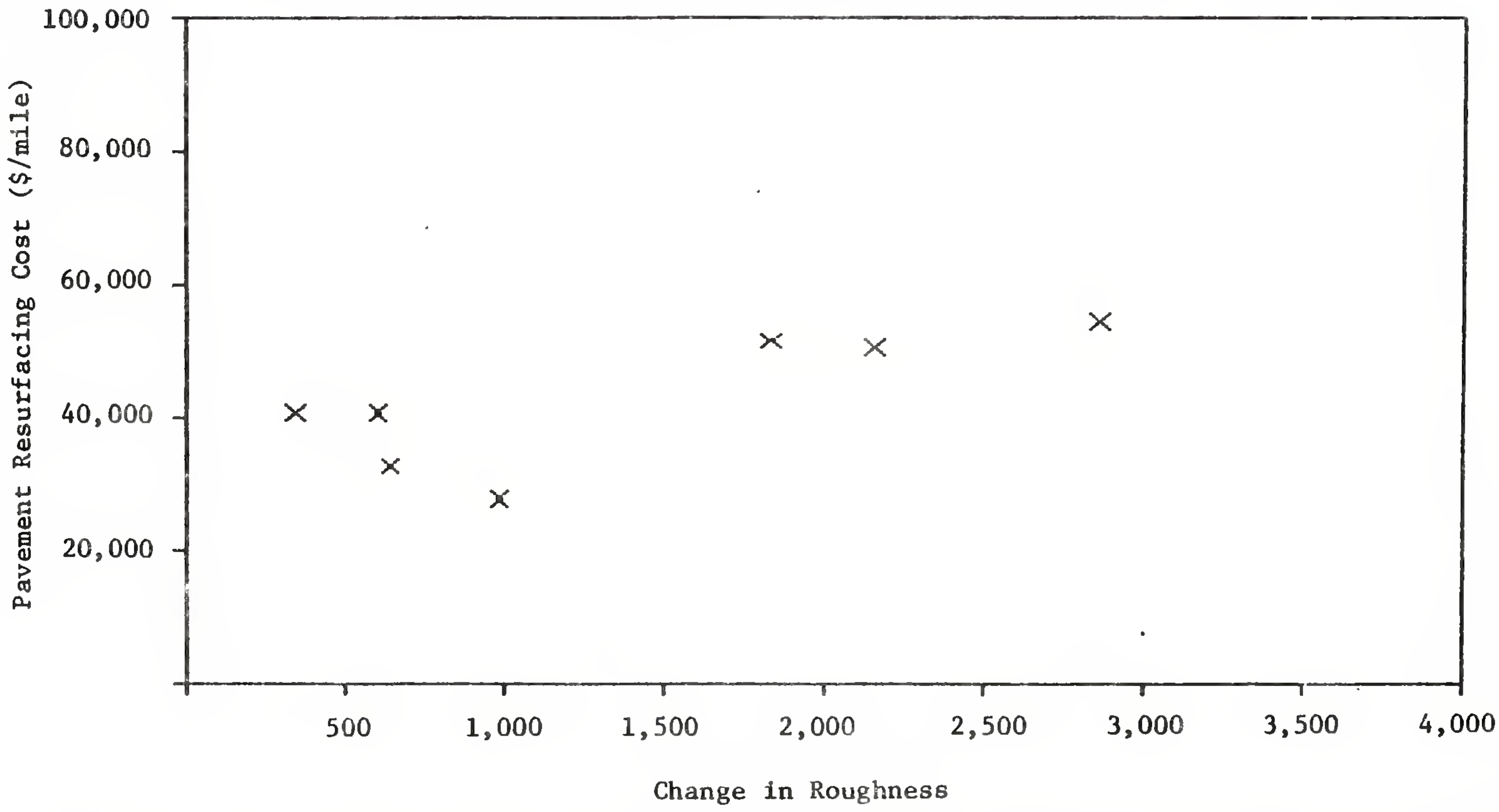


Figure 5.9 Relationship Between Pavement Resurfacing Cost and Change in Roughness for Pavements Resurfaced with HAE Type III During 1982.

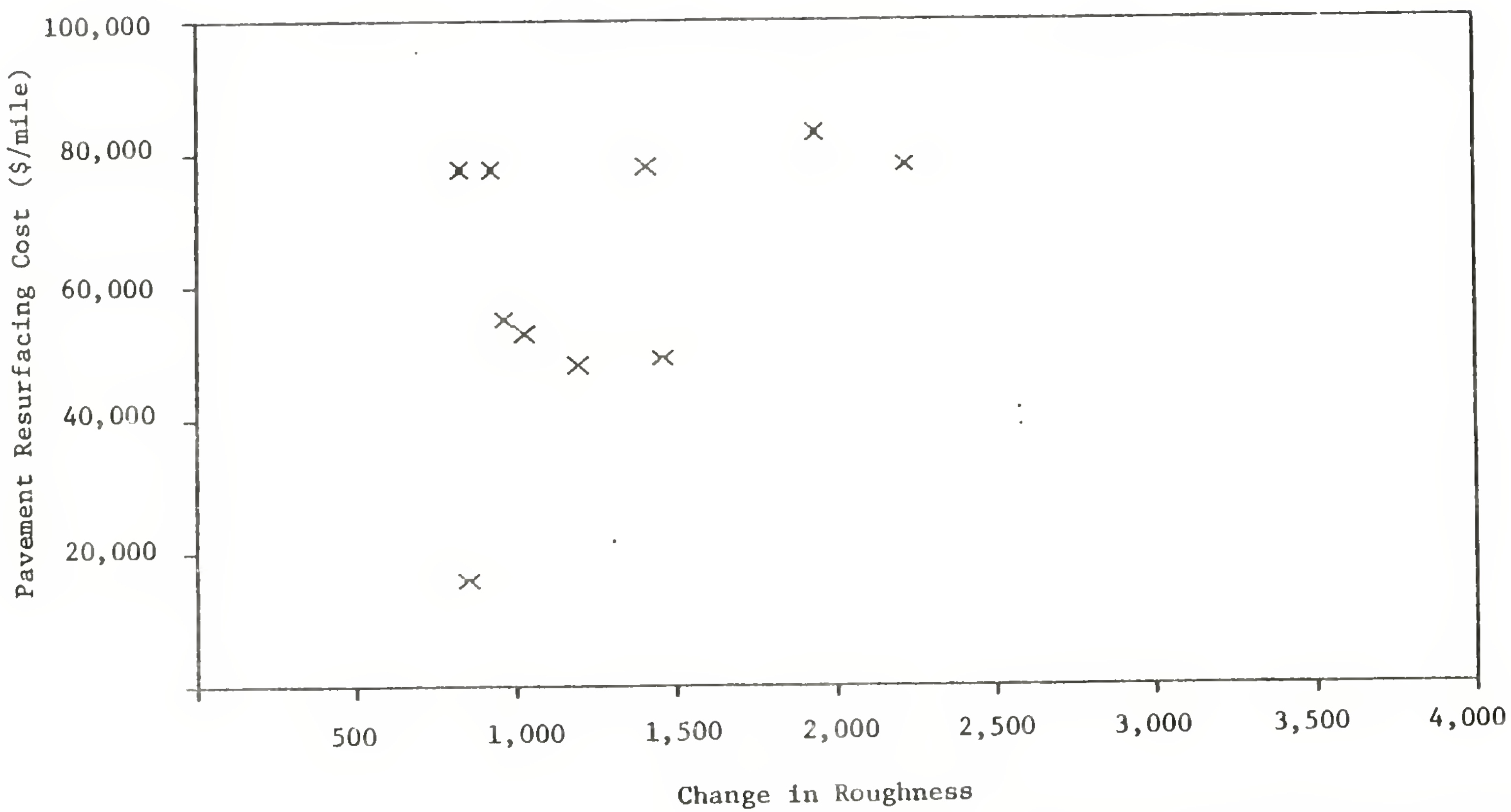


Figure 5.10 Relationship Between Pavement Resurfacing Cost and Change in Roughness for Pavements Resurfaced with HAE Type IV During 1982.

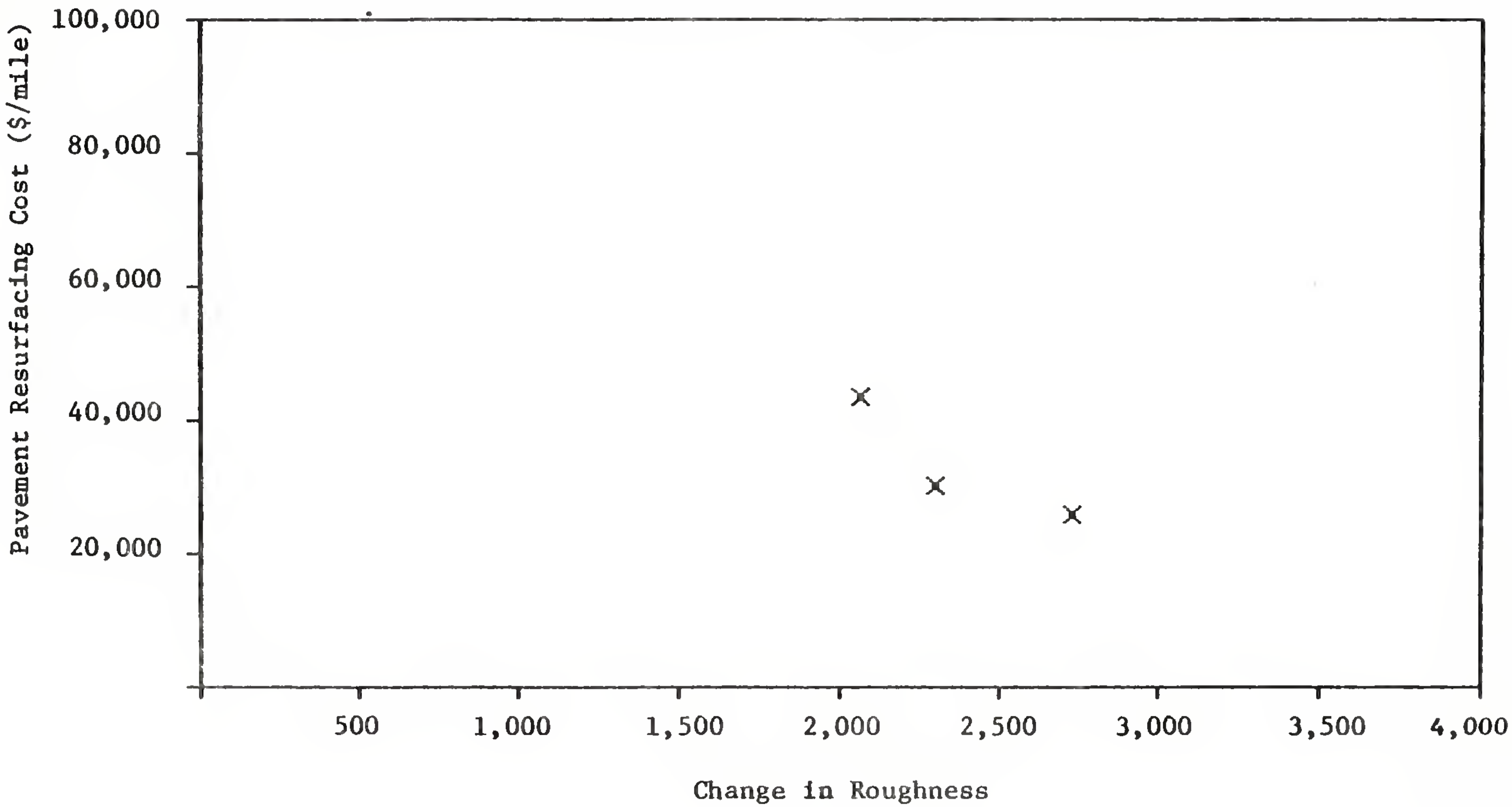


Figure 5.11 Relationship Between Pavement Resurfacing Cost and Change in Roughness for Pavements Resurfaced with HAC Type A During 1982.

2. Hot Asphalt Emulsion Type IV was the only type of surface which showed a slight, but definite relationship between pavement resurfacing cost and change in roughness number (see Figure 5.10).

In order to check how strong was the relationship between percent reduction in roughness number and cost per mile, the following model was tested:

$$TPR = a * (\%\ Red)^{b} \qquad (5.2)$$

where:

TPR = total pavement resurfacing cost, \$/mile;

% Red = reduction in roughness number computed using equation 5.1;

a,b = regression coefficients.

The regression and correlation coefficients obtained from this analysis are also shown on the figures. Although the correlation coefficients obtained from this analysis were quite low, an overall relationship can be noted in the graphs. Data from additional resurfaced sections would be necessary to further confirm the statistical significance of the relationship.

In order to develop a performance function for this study, the contract sections were further grouped according to the seven resurfacing activities conducted in Indiana during 1982. The grouping was done primarily to minimize

the variance among similar homogeneous resurfaced sections. The mean percent reduction in roughness number for each resurfacing group was plotted against the corresponding overlay thickness and a curve of the order shown in Equation 5.2 (see Figure 5.12) was fitted. The final performance function model is shown below:

$$\% \text{ Red} = 61.35 * T^{0.26} \qquad (5.3)$$

$$R^2 = 0.83$$

where:

% Red = Reduction in Roughness Number computed using Equation 5.1;
T = Overlay Thickness, inches.

It should be noted that the model presented in Equation 5.3 is applicable only within the range of thickness shown in Figure 5.12. Any attempt to apply the model above or below this range might give unrealistic results. For example, if the model is applied to a pavement section which has been resurfaced with an equivalent thickness of 5 inches, the percent reduction in roughness number using the model would be 93.22 percent and for 6 inches it would go as high as 97.75 percent. These percent reduction values might be unrealistic in many cases. Even the newly resurfaced pavements have a certain level of roughness, somewhere between 300 and 550 counts per mile.

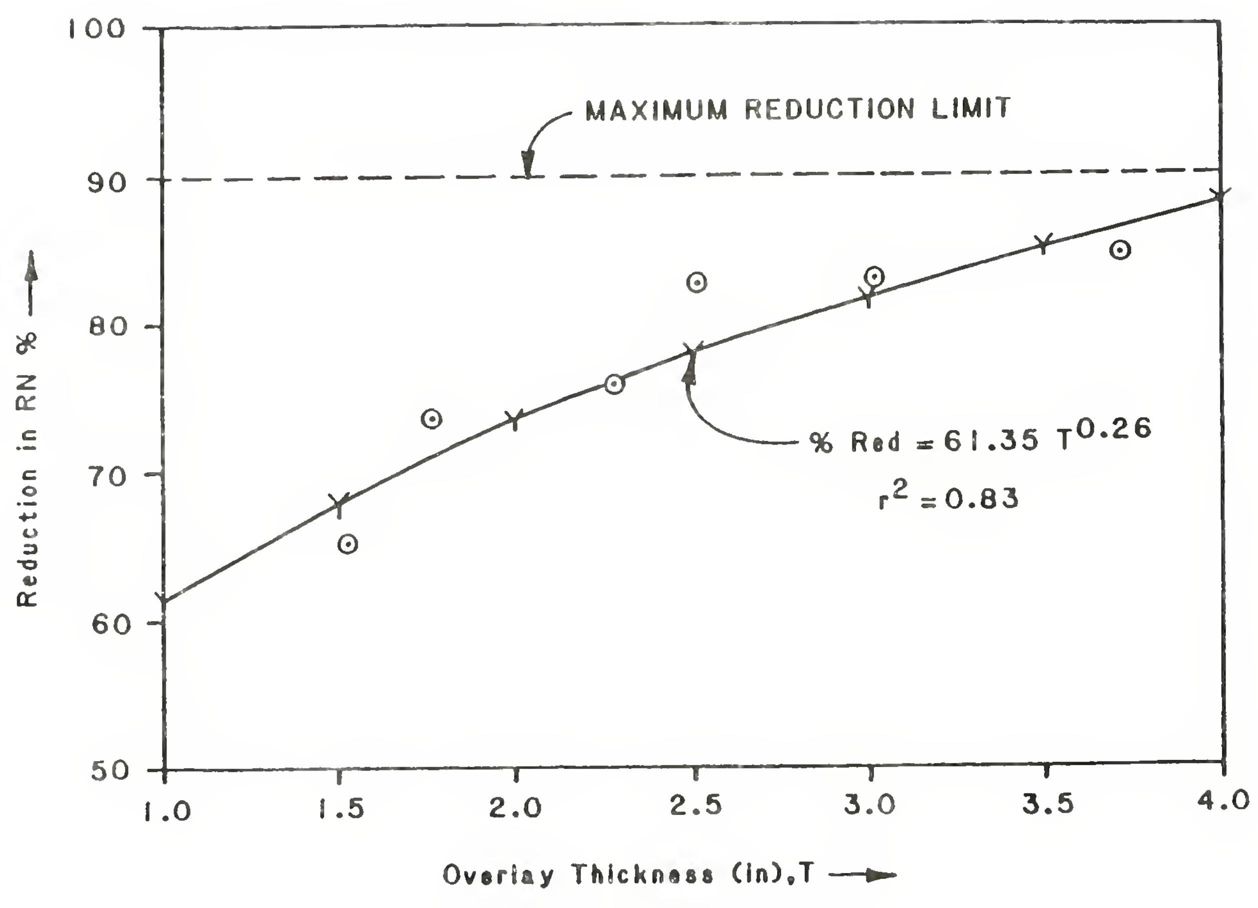


Figure 5.12 Relationship Between Reduction in Roughness and Required Overlay Thickness.

Effect of Resurfacing on Roughness Number

Figures 5.13 and 5.14 show the distribution of roughness number for pavement sections resurfaced during 1981 and 1982, respectively. From these figures it can be noticed that roughness number values after resurfacing follow a multi-modal distribution. In 1982, for example, the first part of the distribution starts at 100 counts per mile and goes to approximately 800. The second part of the distribution starts at about 800 and goes to 1800 counts per mile. The reason behind this form of distributions is that the roughness number after resurfacing is dependent on the roughness prior to resurfacing as well as on the resurfacing strategy adopted. For example, if a pavement section has a very high roughness number, say 4500, and after being resurfaced the roughness is reduced about 77 percent, the new roughness number will probably still be over 1000 counts per mile.

Effect of Surface Type on Roughness Number

An attempt was also made to see whether or not the type of surface course has an effect on the roughness readings recorded by the PCA Roadmeter. Figure 5.15 shows the average roughness number distribution for the different types of surfaces used by the IDOH during 1982. It is interesting to

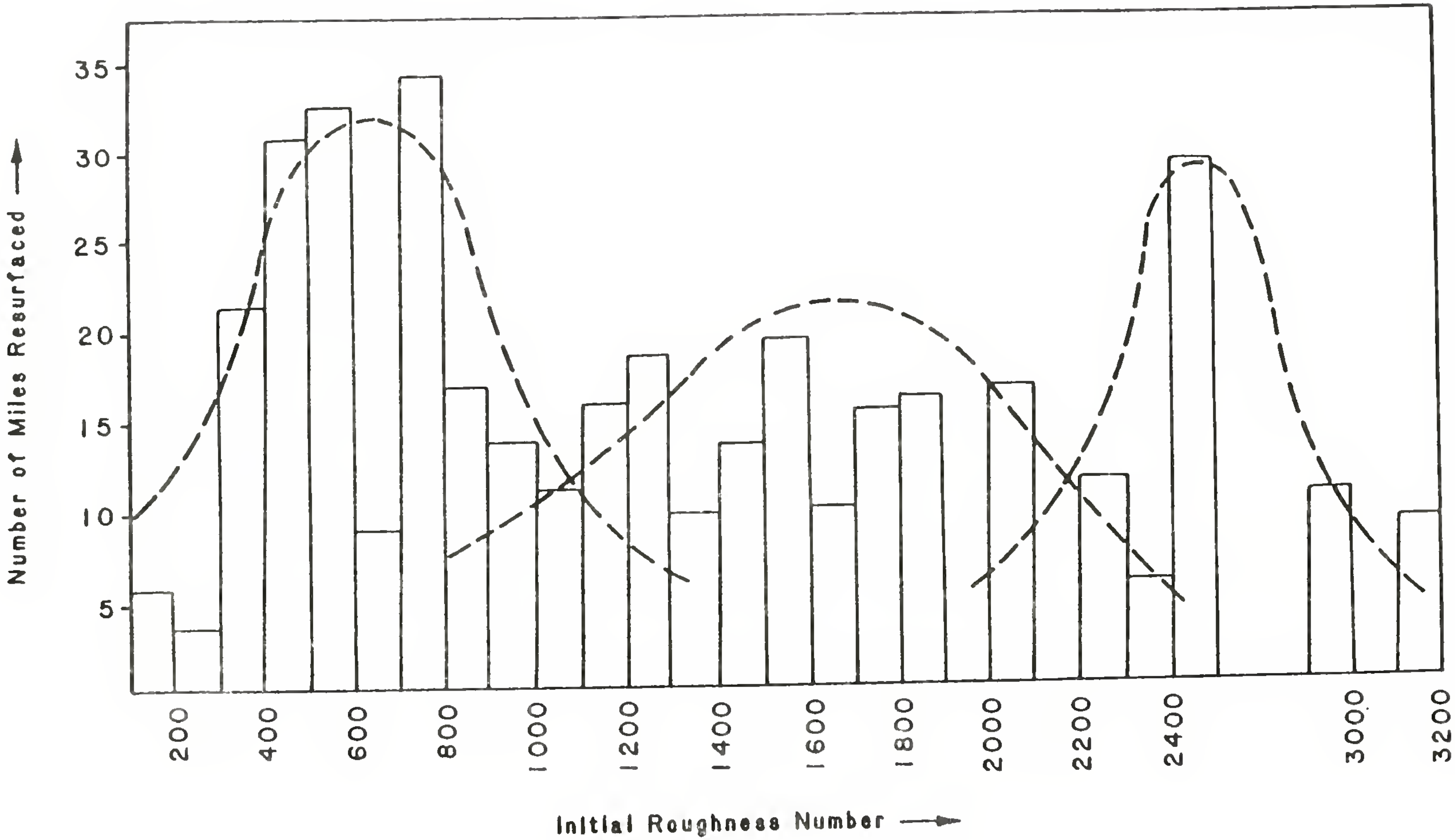


Figure 5.13 Distribution of Roughness Number Measured Just After Resurfacing in 1981.

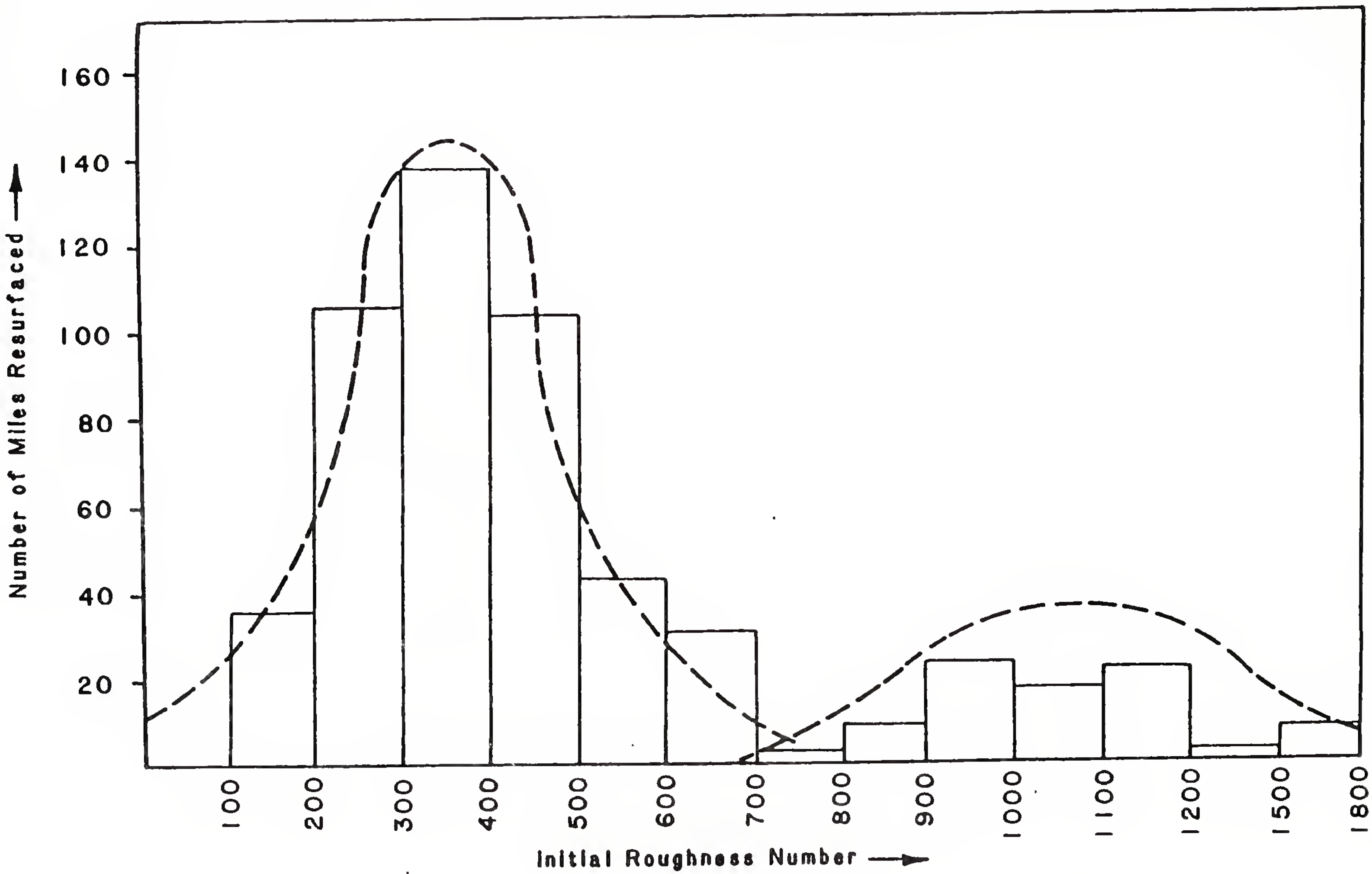


Figure 5.14 Distribution of Roughness Number Measured Just After Resurfacing in 1982.

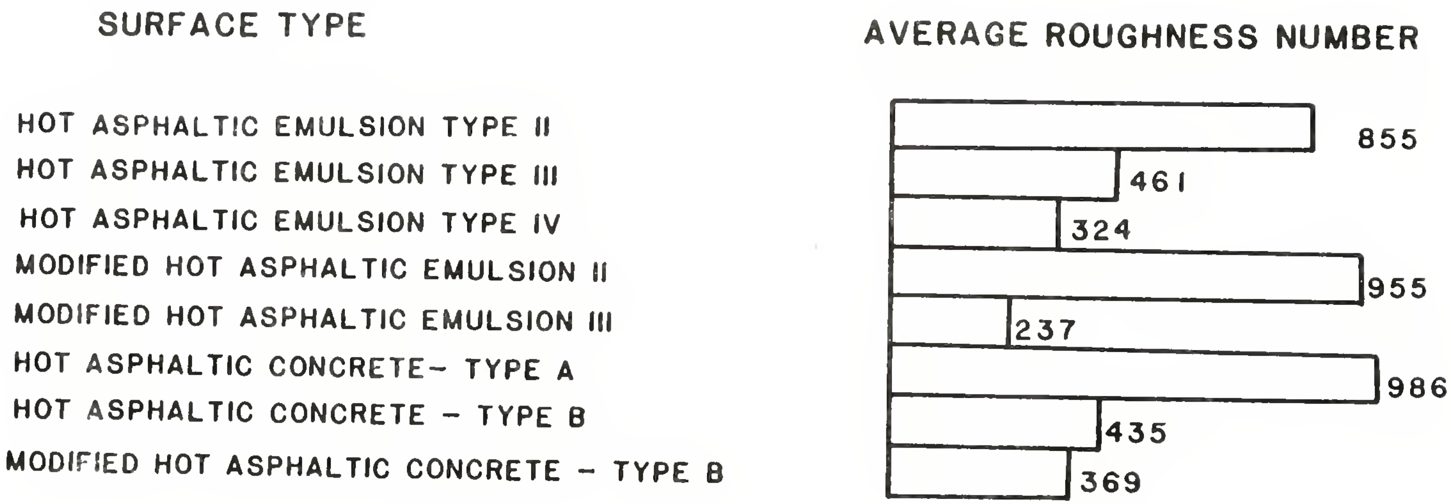


Figure 5.15 Average Roughness Numbers for the Different Types of Surface Used During 1982.

note that the mean roughness number just after resurfacing with a hot asphaltic emulsion (HAE) type III or IV is much lower than that resulting from resurfacing with a hot asphaltic emulsion type II. In addition, the mean roughness number of hot asphaltic concrete (HAC) type B and modified HAC-B are also much lower than that of HAC-A. The reasoning behind this difference in roughness number is as follows: First, HAE type IV is primarily used on high volume roads (i.e. interstates and U.S. routes). It is essentially a sand mix with anti-skid properties, with a very low stability and it develop ruts relatively easily. This surface is in fact smoother as compared to any other surface. In addition, since interstate roads are generally level with gentle grades as compared to many secondary roads, the surface tends to show low roughness readings. However, if the same mix (i.e. HAE IV) is used on pavements with steep grades, the roughness readings may be higher as compared to interstates. The same reasoning is applicable to HAC-B which is also used primarily on interstates and high volume roads. Again, HAC-B is, in fact, a smoother surface as compared to HAC-A. Therefore, it is important to keep in mind that the roughness number is affected by geometrics of the highway and caution should be exercised when using this parameter in the development and application of the optimization model.

Roughness Number Stochastic Characteristics

The roughness number information used in this study are measured on the basis of only one pass of the PCA roadmeter through each pavement section. Therefore, the measurement does not take into account the variations in the readings of the roadmeter device. Previous studies conducted at Purdue have shown that the roughness number obtained using the roadmeter depends upon the following factors [76]:

1. Test Speed
2. State of Suspension System
3. Tire Type and Size
4. Tire Pressure
5. Air Temperature
6. Gas Tank Level
7. Crew Size
8. Wind Velocity
9. Driver Type
10. Highway Geometrics

The stochastic characteristics of the roadmeter can be incorporated into the optimization routine if they are available for each pavement section entered to the problem.

The purpose of this section is two fold:

1. To check whether the variability of the roughness number measurements was more critical for sections that had high roughness numbers as compared to smooth pavement sections.

2. To check whether the variability of the roughness number is more critical on asphalt pavements as compared to jointed reinforced or continuously reinforced concrete pavements. If the observed variability in roughness number is not significant, then the stochastic characteristics need not to be considered in the optimization model.

Selection of Pavement Sections

Twelve one-mile equivalent pavement sections were selected for the analysis. These pavement sections were representative of the entire roughness number spectrum expected in the network covering low and high roughness numbers for both concrete and flexible pavements including overlayed pavements. In each pavement section the driver drove a minimum of five times and recorded roughness measurements. The mean and standard deviation were then computed for the twelve sections and the confidence interval associated with them was determined using a 95 percent confidence band. The results of this analysis are tabulated in Tables 5.1 and 5.2 and are also plotted in Figures 5.16 through 5.18.

Table 5.1 Summary Statistics Pertaining to the Pavement Sections Considered in the Roughness Number Stochastic Analysis (95 percent confidence level)

Section number	Pavmt Type	Mean RN	Std. Dev.	n	$\frac{S(x)}{\sqrt{n}}$	$t(1-\alpha/2,n-1)$	Error	Percent	Date	Location Reference
1a.	AC	796	27.0	8	9.5	2.365	22.6	2.8	4-29-83	Biltz
1b.	AC	866	109.3	5	48.9	2.776	135.7	15.7	5-05-83	Biltz
2a.	AC	1329	89.4	7	33.8	2.447	82.7	6.2	4-29-83	Aretz
2b.	AC	1287	91.2	5	40.8	2.776	113.3	8.8	5-05-83	Aretz
3	JRC	1418	34.5	8	12.2	2.365	28.9	2.0	5-05-83	Salisbury WB
4	CRC	1534	77.4	5	34.6	2.776	96.0	6.3	5-05-83	I-65 SB
5	JRC	1597	61.8	10	19.5	2.262	44.1	2.8	5-05-83	Montmorenci WB
6	JRC	1871	72.7	10	23.0	2.262	52.0	2.8	5-05-83	Montmorenci EB
7	CRC	1904	34.5	4	17.3	3.182	55.0	2.8	5-05-83	I-65 NB
8	JRC	2363	118.8	9	39.6	2.306	91.3	3.9	5-05-83	Salisbury EB
9	overlay	660	14.7	10	4.6	2.262	10.4	1.6	5-05-83	Calibration Site WB
10	overlay	665	27.4	9	9.1	2.306	21.0	3.2	5-05-83	Calibration Site EB
11	overlay	2894	135.2	9	45.1	2.306	104.0	3.6	5-05-83	Duncan West Bound
12	overlay	4044	344.0	8	121.6	2.365	287.6	7.1	5-05-83	Duncan East Bound

Table 5.2 Confidence Intervals for the Pavement Sections Used in the Roughness Number Stochastic Analysis

Pavement Section	Pavement Type	Lower Interval	Mean Roughness	Upper Interval	Percent Error
1a	AC	773.4	796	818.6	2.8
1b	AC	730.3	866	1001.7	15.7
2a	AC	1246.3	1329	1411.7	6.2
2b	AC	1173.7	1287	1400.3	8.8
3	JRC	1389.1	1418	1446.9	2.0
4	CRC	1438.0	1534	1630.0	6.3
5	JRC	1552.9	1597	1641.1	2.8
6	JRC	1819.0	1871	1923.0	2.8
7	CRC	1849.0	1904	1959.0	2.8
8	JRC	2271.7	2363	2454.3	3.9
9	OVERLAY	649.6	660	670.4	1.6
10	OVERLAY	644.0	665	686.0	3.2
11	OVERLAY	2790.0	2894	2998.0	3.6
12	OVERLAY	3756.4	4044	4331.6	7.1

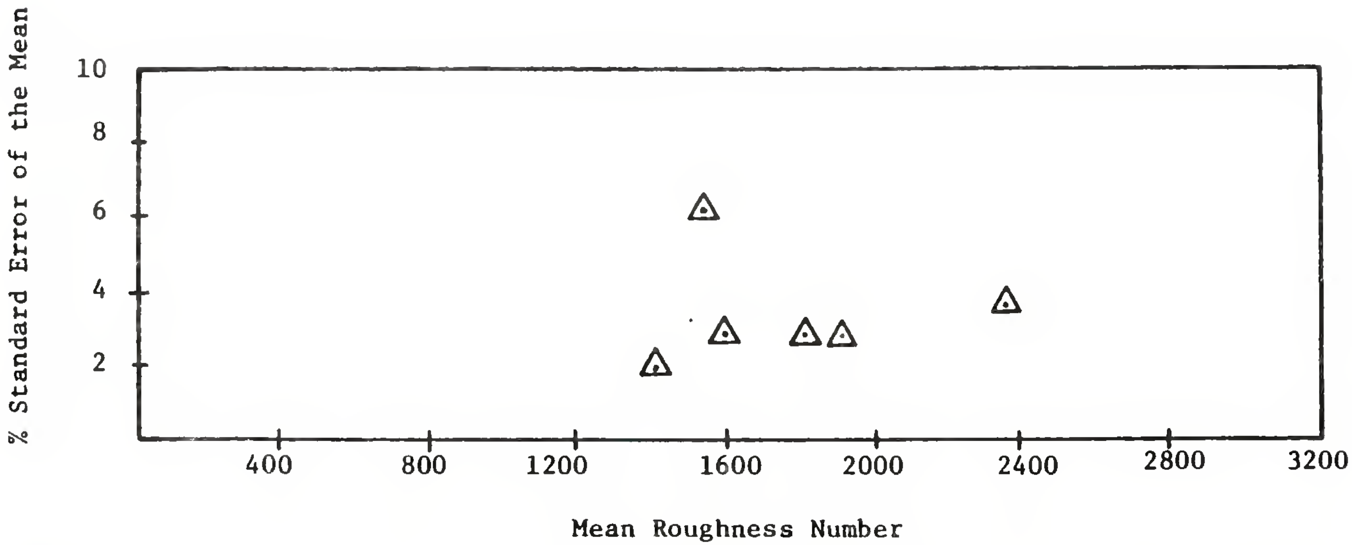


Figure 5.16 Relationship Between % Standard Error of Mean and Mean Roughness Number for Concrete Pavements

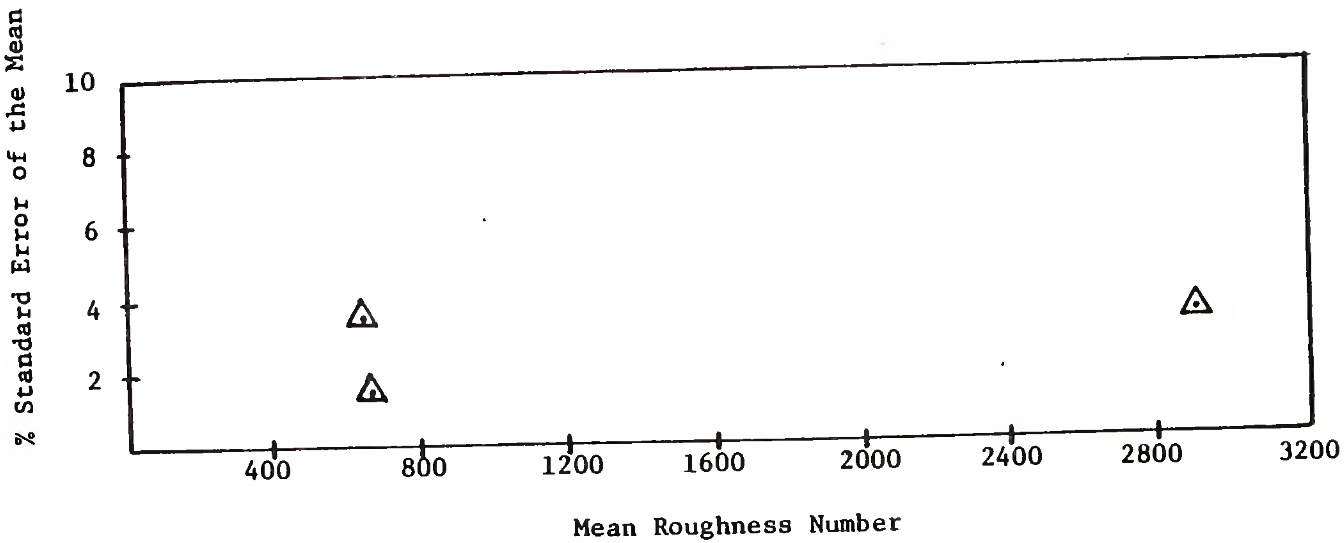


Figure 5.17 Relationship Between % Standard Error of Mean and Mean Roughness Number for Overlayed Pavements

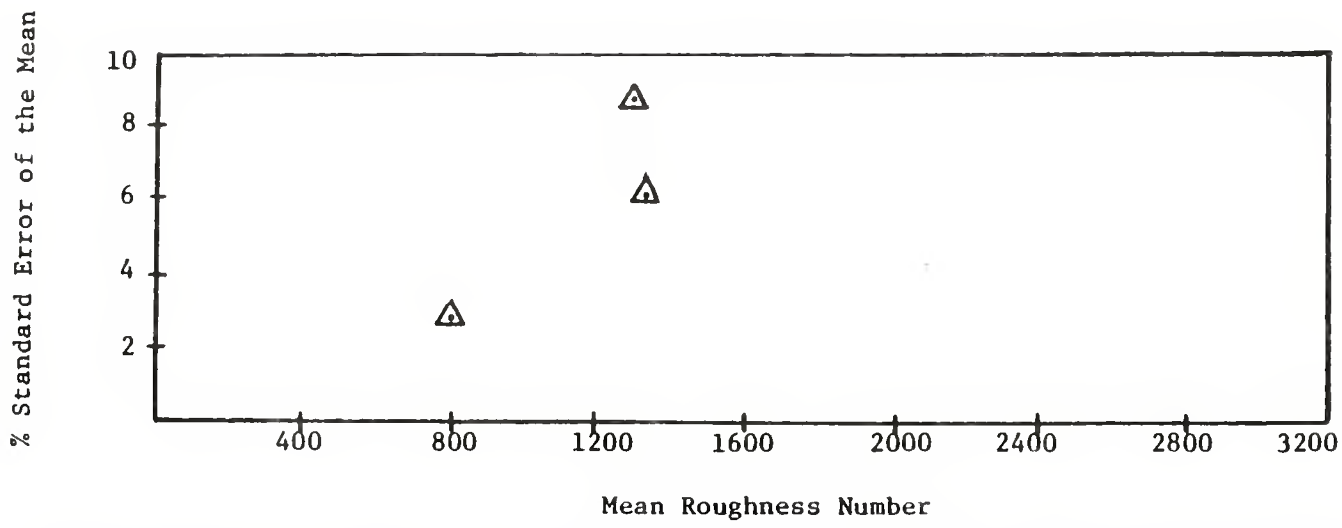


Figure 5.18 Relationship Between % Standard Error of Mean and Mean Roughness Number for Asphalt Concrete Pavements

Discussion of Results

In order to check whether the variation in roadmeter reading is dependent upon how rough is the pavement at the time of the test, the percent error of each pavement section was computed using the following equation:

$$\% E_i = \frac{s(x)_i}{\sqrt{n}} * \frac{t(1 - \alpha/2, n-1)_i}{MRN_i} \tag{5.4}$$

where:

E_i = percent standard error of mean associated with pavement section i;

n = number of times roughness number was measured on pavement section i;

α = significant level taken as 0.05;

MRN_i = mean roughness number for pavement section i, $\frac{\sum_{j=1}^{n} RN_j}{n}$;

RN_j = roughness numbers measured on each pavement section;

$t(1- \alpha/2,n-1)_i$ = t distribution percentiles associated with pavement section i;

$s(x)_i$ = standard deviation of pavement section i.

Based on Figure 5.16 it can be noted that the percent error of the mean roughness number for concrete pavements is almost uniform irrespective of the magnitude of the roughness number. In most cases the percent error was between 2 and 4 percent. This fact is very important since it indicates that the variability of the roadmeter is almost constant irrespective of the roughness magnitude, low or high.

For overlayed pavements the same observation can be made since the percent error was always between 1.5 and 4.0 percent for the entire roughness number spectrum (see Figure 5.17).

On the other hand, for asphalt pavements the above statement is not entirely appropriate since, based on the test sections evaluated, it appears that high roughness numbers might have a larger variance associated with them (see Figure 5.18).

Further research is necessary in this area to ensure that roughness variability is not significant.

CHAPTER 6

DEVELOPMENT AND FORMULATION OF OPTIMIZATION MODELS

Introduction

This chapter demonstrates how the integer programming technique was used in this study to formulate the two optimization models developed as a part of this study. The parameters used as input to the optimization models are briefly discussed. A description of the Branch and Bound technique which was finally adopted for solving the integer programming formulations is explained including a simplified example. A discussion of the computer codes available at Purdue University to solve integer programming problems is also included along with their capabilities and limitations.

It should be noted that the initial conceptual framework of the optimization model developed in this study was influenced by the approach proposed by Sinha, Kaji, and Liu [84], and Muthusubramanyan, Sinha and Ravindran [62,63,64].

Model Parameters

Decision Variable

The Indiana Department of Highways (IDOH) is primarily interested to determine the number of miles that can be rehabilitated with the limited resources available, such as budget, materials, equipment, and so on, in any given year. In particular, it is necessary to identify the exact location and length of those pavement sections which are in immediate need of a major rehabilitation including the type of most cost-effective rehabilitation during a given period of time. Paving contract section appears to be the ideal unit to represent the decision variables in this study since pavement characteristics such as pavement thickness, width, age, drainage, materials, construction method, and so on are, in most cases, homogeneous throughout the entire section.

The actual number of decision variables associated with the optimization model is dependent upon the following factors:

1. Number of contract sections
2. Number of maintenance activities
3. Number of years in the analysis period

The mathematical notation used to represent the decision variable is x_{ijk}. The subscript i indicates contract section. The subscript j is used to represent feasible rehabilitation activities applicable to contract section i. The subscript k represents the year in which the contract section i is chosen for implementation of resurfacing activity j. For example, x_{6d1} represents contract section '6', maintenance activity 'd' and first year of the analysis period.

The decision variables used in this model can only take the value of 0 or 1. For example, if x_{6d1} takes the value of 1, it means that contract section 6 has been chosen for rehabilitation with resurfacing activity 'd' in the first year of the analysis period. If x_{6d1} takes a value of 0, then this particular pavement section will not be rehabilitated with resurfacing activity 'd' in the first year. However, it can be rehabilitated with another resurfacing activity during the first year or can be chosen for rehabilitation during any of the subsequent four years. For example, it can be chosen for rehabilitation in year 3 with the same rehabilitation activity that was previously rejected in year 1 (x_{6d3}). If the contract section is not selected for rehabilitation during any of the five years of the analysis

period, then all the decision variables starting with the subscript 6 will take the value of 0.

In order to compute the total number of decision variables to be included in the optimization model, the following equation is used:

$$NVAR = NREHAB \sum_{i=1}^{nyear} CS_i * (nyear+1-i) \qquad (6.1)$$

where:

NVAR = total number of variables;

NREHAB = number of feasible rehabilitation activities;

CS_i = number of deficient contract sections at the beginning of year i;

nyear = number of years in the analysis period.

Pavement Resurfacing Activities Considered

The pavement resurfacing activities considered in this study were selected after inspecting the final construction records of the Indiana Department of Highways for fiscal years 1980, 1981, and 1982. A total of seven resurfacing activities were finally selected. The average costs per center-line mile associated with each resurfacing activity, in terms of 1982-1983 dollars, are shown in Table 6.1.

A total of three resurfacing activities were finally assigned to each pavement section input to the model. The

Table 6.1 Pavement Resurfacing Costs and Routine Maintenance Costs Assigned to the Resurfacing Strategies Considered in the Optimization Model

Resurfacing Strategy inches (lbs/sys)	Pavement Resurfacing ($/center-line mile)	Routine Maintenance Cost ($/center-line mile/yr)
1.0" (110)	310,000.00	900.00
1.5" (175)	345,000.00	765.00
2.0" (70+135)	371,000.00	635.00
2.5" (70 +220)	393,000.00	500.00
3.0" (110+220)	412,000.00	365.00
3.5" (70 +135+175)	429,000.00	235.00
4.0" (70 +175+175)	445,000.00	105.00

criterion used to assign the resurfacing strategy to a particular pavement section was a function of the current traffic of the facility. The details pertaining to the assignment of resurfacing strategies to pavement sections in the model are explained in Chapter 7.

It should be mentioned that most of the rehabilitation projects conducted on distressed pavements in Indiana are primarily resurfacing with either a hot asphaltic emulsion or a hot asphaltic cement with different grades. The type of asphaltic material used for the surface course is dependent, in most cases, upon the highway district in which the pavement section is located and also upon whether the pavement section is classified as an interstate or as a Federal-aid primary or secondary system.

It is also important to point out that the pavement resurfacing cost for a particular section can also vary with the number of lifts involved in placing the surface course. For example, the resurfacing cost associated with a surface course constructed with two passes of 175 lbs. per square yard is more expensive than a surface course with only one pass of 350 lbs. per square yard. Both surface courses, however, are equivalent to approximately 3 inches of overlay.

It should be mentioned that the cost figures used in this study are based on total project costs and not only on pavement cost. Therefore, there may be two pavement sections with the same pavement thickness and the same length, but the difference in project costs may be as high as $40,000 to $60,000, depending upon the extent of non-pavement work performed under the same RS-contract funds. Furthermore, it should be kept in mind that the cost figures used in this study are average figures of the entire interstate highway network and, therefore, should be treated as such.

Pavement Routine Maintenance Costs Considered

Pavement routine maintenance costs are also included into the optimization model. Every pavement section that is selected by the optimization model for resurfacing during the analysis period is assumed to have some routine maintenance every subsequent year after being resurfaced. The pavement routine maintenance costs used were obtained from findings of another research study being conducted at Purdue University [94]. In that study it was estimated that the range in pavement routine maintenance costs for interstate reinforced concrete pavements ranged between 50 and 500 dollars per lane-mile per year based on 1982-1983 dollars. Pavement age and accumulated 18 kip axle loads were found to be the most significant variables in predicting pavement

routine maintenance. For the purpose of the present study, future pavement routine maintenance costs were estimated based on the above range for the seven resurfacing strategies considered in the optimization model.

Budget Information

Accurate information pertaining to the annual budget assigned to pavement resurfacing activities in Indiana was difficult to obtain. This was because there are many different sources of money for pavement resurfacing projects. Some of these are:

1. Roads (R) and Resurfacing (RS) contracts
2. Rehabilitation, Restoration, Resurfacing, Reconstruction Funds (4-R funds)
3. Major Capital Improvement Funds

However, there are different sources from which budget estimates can be made. The sources used for this study are listed below:

1. IDOH Biennial Report, FY 1984-85 [95]
2. IDOH Planning Division
3. Other Sources [15].

The data from various sources were extrapolated to predict future budget for the analysis period being considered.

Analysis Period

The analysis period is the time frame in which the proposed model is to be applied. In this study, a time frame of 5 years was used since most states are required to prepare their highway improvement plan for a 5 year period. The output of the proposed formulation should be useful in assisting those in charge of preparing a multi-year program to better estimate the amount of miles that can be rehabilitated with the given program budget. The effect of increasing the funding level upon the additional number of miles of rehabilitation is also an important information for programming. The proposed modelling approach can also be used to estimate the optimal level of budget required to bring the pavement network to a certain condition level at the end of the analysis period.

Constraints

Constraints are restrictions which are input to the model in order to consider the operational limitations. For example, one cannot assign two rehabilitation activities on a particular contract section in the same year. Another constraint can be that the total cost associated with the entire resurfacing program during a particular year cannot exceed the total available budget for that year. The

details pertaining to the constraints included in the proposed formulation are described later in this chapter.

Decision to Use the Integer Programming Technique

The primary reason for using the zero-one integer programming technique in this research project is threefold. First, this optimization technique is very useful and practical in those cases where the decision makers are interested in knowing whether or not a particular pavement section should be chosen for major rehabilitation in a given year and, if so, what resurfacing activity should be applied in order that the distribution of available funds within that year are allocated in a cost-effective manner. Second, this technique is easily understood. Third, the availability of computer codes for solving integer programming formulations makes this technique even more attractive for this task. In essence, the main advantage of using the integer programming technique is that it closely replicates the real world decision process.

Description of the Branch and Bound Method

The zero-one integer programming technique uses an efficient enumeration procedure, known as the Branch and Bound algorithm, to arrive at the optimal integer (zero-one) solution [96]. In order to better understand the procedure used by the branch and bound technique, the following example is presented. Let us assume that the optimization model consists of the objective function 'Z' and constraints, as shown below [90]:

$$\text{Maximize } Z = 75x_1 + 6x_2 + 3x_3 + 33x_4 \tag{6.2}$$

$$\text{subject to: } 774x_1 + 76x_2 + 22x_3 + 42x_4 \leq 875 \tag{6.3}$$

$$67x_1 + 27x_2 + 794x_3 + 53x_4 \leq 875 \tag{6.4}$$

The initial step of the branch and bound method is to solve the current formulation as a continuous linear programming model but with the addition of constraints in the form $x_i \leq 1$ to take into account that the integer variable in question cannot be greater than one. The next step is to check whether the continuous LP solution at this stage is completely integer (i.e. zero-one value). If this is the case, no further analysis is necessary and this becomes the optimal integer solution. On the other hand, if any of the the expected integer variables is assigned a fractional value, the algorithm arbitrarily selects one of them as the

branch variable. For the above example, after the LP solution was calculated, it was found that variables x_1 and x_4 were assigned a value of one, and x_2 and x_3 were assigned a fractional value. At this stage the original linear programming (LP) formulation is replaced by two new formulations, one formulation will have the constraint $x_2 = 0$ added to the constraints of the original formulation, while the other formulation will be appended with the constraint $x_2 = 1$. The algorithm then solves these two new formulations as LP. If it is a maximization problem, the formulation which gives the highest value of the objective function is the best solution for the original formulation.

The use of the term "branch" is simply because each new formulation which is created corresponds to a branch in an enumeration tree (Refer to Figure 6.1). If fractional variables are encountered in the two new formulations, further branching (partitioning) is performed until the value of the objective function is less than the value of another integer (zero-one) solution previously encountered in another branch. At this stage the optimal integer solution is achieved and this solution represents the "bound" for all feasible integer solutions. The value of the objective function of the integer solution previously computed in another branch becomes a lower bound on the maximum value of

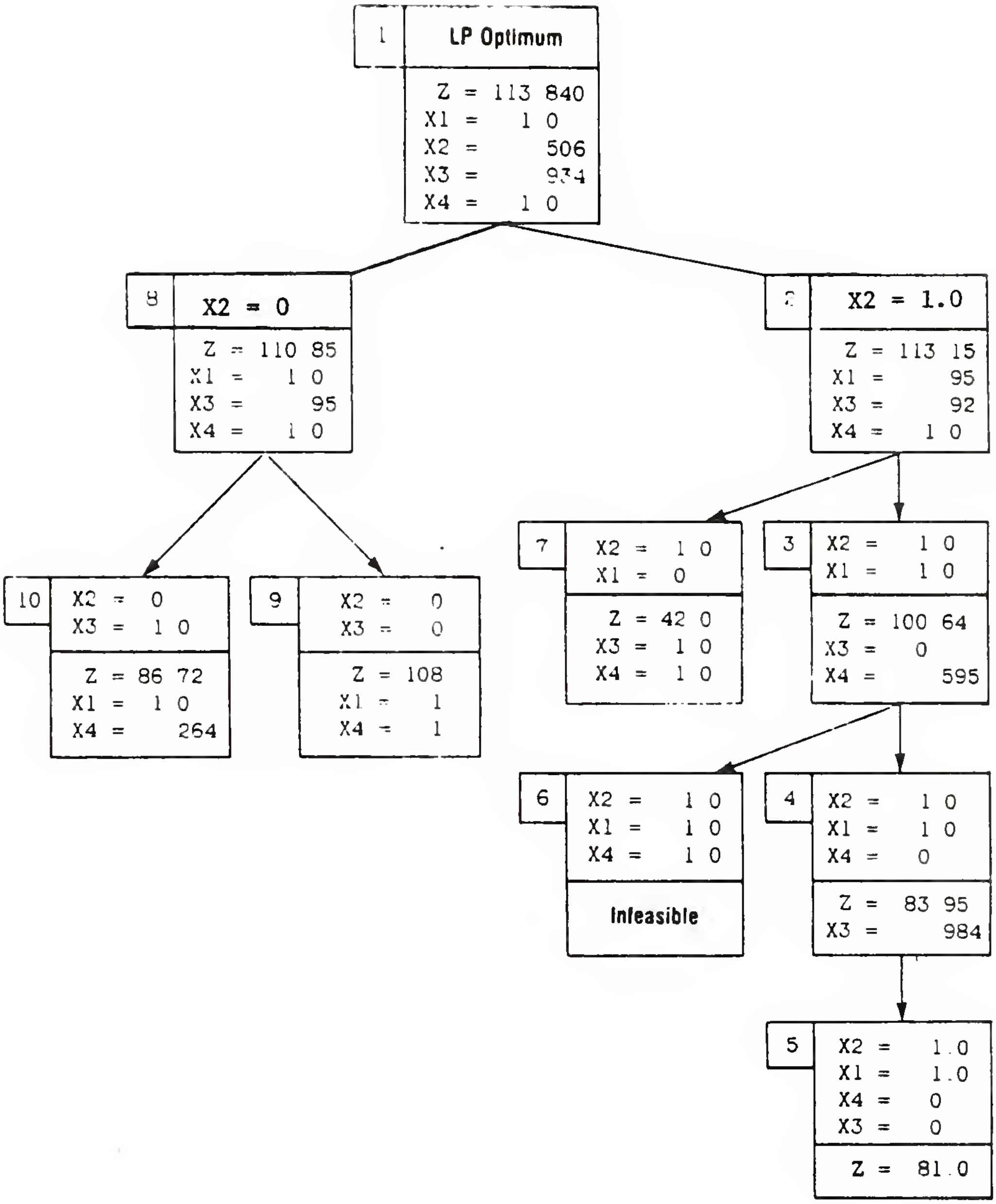


Figure 6.1 Illustrative Example of the Branch and Bound Technique. [90]

the objective function. In other words, the optimal integer value of the objective function cannot be less than this value. It is important to mention that each time a new constraint is added at a particular branch, the value of the objective function will be decreased in the subsequent branching. In other words, the objective function cannot be improved as one moves within its branch.

Model Formulations Considered

Two model formulations were considered in this study. The first formulation, referred in this study as the contract section worth model, uses the weighed reduction in pavement distress over a five year period as the measure of effectiveness.

The second model formulation, referred in this study as the roughness reduction model, uses the total reduction in roughness number for each pavement section as the new measure of effectiveness.

Trigger values associated with asphalt and concrete pavements were used to identify sections with high roughness number, and only those sections were included in the optimization model.

Contract Section Worth Model

The objective function coefficients for the contract section worth model were constructed by multiplying the following three factors:

1. Contract Section Worth (CSW)

2. Percent reduction in pavement roughness caused by a particular resurfacing type.

3. Traffic growth rate and rate of increase in roughness for each contract section.

The worth of each contract section CSW_i was calculated as follows:

$$CSW_i = TADT_i [(1-RNEPI_i)(WRN)+(1-\Delta RNEPI_i)(W\Delta RN)+ (1-AGEEPI_i)(WAGE)+(1-PCI_i)(WPCI)] \tag{6.5}$$

where:

CSW_i = worth of contract section i;

$TADT_i$ = accumulated average daily traffic in one direction for contract section i in veh/day;

$RNEPI_i$ = roughness number equivalent performance index for contract section i ($0 < RNEPI < 100$);

WRN = roughness number's relative weight ($0 < WRN < 1$);

$\Delta RNEPI_i$ = the equivalent performance index for change in roughness for contract section i,

($0 < \Delta RNEPI < 100$);

$W\Delta RN$ = relative weight of change in roughness number, ($0 < W\Delta RN < 1$);

$AGEEPI_i$ = pavement age equivalent performance index for contract section i;

WAGE = relative weight assigned to pavement age, ($0 < WAGE < 1$);

PCI_i = pavement condition index for contract section i, ($0 < WPCI < 100$);

WPCI = relative weight assigned to pavement condition index, ($0 < WPCI < 1$).

The average daily traffic of each contract section was obtained from the latest traffic flow maps published by the Planning Division of Indiana Department of Highways [67]. The total accumulated ADT of each contract section was computed using the directional ADT and Equation 3.1 shown in Chapter 3.

The equivalent performance indices for roughness, change in roughness, and pavement age for each contract section were estimated after interpolating the appropriate performance curves. The development of these curves has been discussed in Chapter 3.

Performance curves were developed for conventional asphalt pavements, jointed reinforced and continuously reinforced pavements. Two sets of curves were developed, one for interstate system and the other for Federal-aid primary and Federal-aid secondary system. The relative weights for roughness, change in roughness number, pavement age, and pavement condition index were estimated in consultation with members of IDOH Pavement Management Task Force Committee. These weights reflect the relative importance of each of the performance factors considered in the formulation.

It would have been more desirable to use the total 18 kip Equivalent Axle Loads as the traffic parameter rather than just total ADT. However, this information is not currently available for all the contract sections in the state.

Since traffic is an important factor in the selection of a highway section for major rehabilitation, it was decided to give this factor the same weight as the combination of other parameters. This was done by multiplying the accumulated ADT by the summation of the individual effects attributed to the other parameters.

The contract section worth model is shown below:

$$\text{Max } Z = \sum_{i=1}^{n} \sum_{j \varepsilon A_i} \sum_{k=1}^{nyear} G_{ik}\ CSW_i\ RED_j\ x_{ijk} \tag{6.6}$$

subject to:

$$\sum_{i=1}^{n} \sum_{j \varepsilon A_i} IF_k\ [L_i\ TRC_j\ [x_{ijk} - x_{ijk-1}] + L_i\ RMC_j\ x_{ijk}] \leq B_k \tag{6.7}$$

$$\sum_{j \varepsilon A_i} x_{ijk} \leq 1 \qquad \text{for all } i \text{ and } k \tag{6.8}$$

$$\sum_{j \varepsilon A_i} x_{ijk} > x_{ijk-1} \qquad \text{for all } i,\ k \text{ and } j \varepsilon A_i \tag{6.9}$$

where:

RED_j = percent reduction in pavement roughness if resurfacing activity j is selected;

x_{ijk} = 1 if contract section i receives resurfacing activity j in year k

= 0 otherwise;

L_i = length of contract section i (miles);

TRC_j = total resurfacing cost associated with activity j in 1982-83 dollars per center-line mile;

RMC_j = annual routine maintenance cost associated with resurfacing activity j in dollars per center-line mile;

$j \varepsilon A_i$ = resurfacing activity j which is one of the set

of three feasible alternatives for pavement contract section i, A_i;

B_k = available budget for the k^{th} year;

G_{ik} = growth deterioration factor for contract section i in the k^{th} year, RN(k)/RN(k-1);

IF_k = inflation factor, $(1+i)^k$;

i = interest rate used, 6 percent;

n = total number of deficient pavement contract sections;

nyear = number of years in analysis period.

Equation 6.6 states that the product of the contract section worth (as defined in Equation 6.5) and percent reduction in pavement roughness should be maximized. An additional parameter, G_{ik}, is included as part of the objective function coefficient to take into account the annual deterioration rate associated with each contract section. This factor was computed as the ratio of the present roughness number and the roughness number of the previous year. If the growth factor computed with the above equation was found to be less than a unity for any particular pavement section, the factor was then reset to one. The primary reason for setting a lower bound on this factor is because each pavement section entered into the model was assumed to be a truly defective section; therefore, this section can be

expected to continue to deteriorate as it passes from one year to another.

Equation 6.7 represents the constraint that the total cost of all rehabilitation projects to be implemented must not exceed the available resurfacing program budget for each of the fiscal years in the analysis period.

Equation 6.8 indicates that no more than one rehabilitation project can be selected among alternative project types for a contract section in a given year.

Equation 6.9 assures that if a rehabilitation project has already been implemented in a previous year, only the routine maintenance task of that particular resurfacing activity will be performed in the current year. For example, if a 4" overlay has been applied to contract section RS-8001 during 1983, only routine maintenance will be performed on this section in 1984 and rest of the analysis period. However, it is important to note that the routine maintenance cost associated with a 4" overlay is not necessarily the same as with a 3" or a 2" overlay. This is the main reason for introducing this constraint into the model.

In addition, Equations 6.8 and 6.9 imply that, at most, only one rehabilitation project is selected for each contract section during the analysis period.

The parameters used in the computation of the objective function coefficients play a very important role in the results obtained by the optimization procedure. In the contract section worth model discussed earlier, the objective function coefficients was computed as the product of the contract section worth (CSW), the percent reduction in pavement distress associated with a particular resurfacing strategy, and the growth factor which takes into account the increase in roughness number during the analysis period. The contract section worth was the primary parameter that reflected the impact of selecting a particular pavement section versus another. It was assumed that all performance factors associated with each pavement section can be aggregated into a composite linear weighed factor such as the contract section worth factor. The effect of selecting a particular resurfacing strategy, however, was measured in terms of roughness. The implicit assumption was that the factors included in computing the contract section worth are directly related to roughness and that the change in contract section worth is proportional to the expected change in roughness. It can be argued that this assumption is not entirely valid because of the non-linearity of some of the factors. A more direct approach would be to consider a single factor representing pavement performance. This factor can be a measurable factor such as roughness, or a derived

factor such as pavement condition index. However, in the present study the effectiveness of alternative resurfacing strategies was measured in terms of change in roughness number. This was done because the IDOH has a roughness data collection program that provided a ready source of information to monitor and evaluate the effectiveness of various resurfacing strategies. The roughness number can be measured within a relatively short period of time and, if properly calibrated, can also be used to develop the performance equation required to take into account the deterioration of the pavement during its design life. Consequently, it was decided to formulate another alternative optimization model in which the objective function was to maximize reduction in roughness in the entire highway system under consideration.

Roughness Reduction Model

The roughness reduction model was formulated in this study as an alternate model for the IDOH pavement management system. The model, in its present form, uses the present roughness number of each contract section along with the variable that represents the percent reduction in roughness number associated with a particular resurfacing strategy and the rate of increase in roughness number for each contract section to compute the objective function coefficient. The only difference between the contract section worth model and

the roughness reduction model is that the contract section worth factor was replaced with the present roughness number. The total reduction in roughness number for each pavement section after the application of a particular resurfacing strategy is the new measure of effectiveness. The objective function for the roughness reduction model is shown below:

$$\text{Max } Z = \sum_{i=1}^{n} \sum_{j \in A_i} \sum_{k=1}^{nyear} RN_i \; G_{ik} \; RED_j \; x_{ijk} \qquad (6.10)$$

where:

RN_i = present roughness number for contract section i;

G_{ik} = roughness increase rate for contract section i; in the k^{th} year;

RED_j = percent reduction in pavement roughness if resurfacing activity j is selected;

x_{ijk} = 1 if contract section i receives resurfacing activity j in year k;

nyear = number of years in analysis period;

n = total number of deficient pavement contract sections.

The constraints of the roughness reduction model remain the same as in case of the contract section worth model. The application of these optimization models is shown in the following chapter.

Description of Available Computer Codes

There are several computer codes available at Purdue University for solving integer programming problems. In the following paragraphs these computer codes are briefly described along with their capabilities and limitations.

MIPZ1

MIPZ1 is a mixed integer programming package developed by the Department of Agricultural Economics at Purdue University [86]. The algorithm is basically a refinement of Balas' Additive Algorithm [87]. At the present time it can be used to solve problems with up to 150 constraints and 450 zero-one integer variables. The data used as input to the program must be entered in MPS format. The access to this program is through the Purdue University CDC machine.

MPOS

MPOS is an optimization package developed at Northwestern University to solve optimization problems on CDC 6000 and CYBER 205 computer [89,90]. It was developed in such a way that the formulation of a particular problem can be stated in plain English and algebraic notation. Several integer, linear, and quadratic algorithms are included in the package. These are:

1. Branch and Bound Mixed Integer Program (BBMIP)
2. Direct Search Zero-One Integer Programming (DSZ1IP)
3. Gomory's Cutting Plane Program (GOMORY)

LINDO

LINDO is an interactive computer package developed at the University of Chicago by Schrage for solving integer, linear, and quadratic programming problems [89,90]. At the present time it can be used to solve problems with up to 1100 constraints and 4000 variables. The data can be entered in different ways. For example, it has interfaces for Mathematical Programming System (MPS) files, written FORTRAN subroutines, and for Benders decomposition for integer programming problems. The access to this computer code is through the Purdue University's Engineering Computer Network (ECN) VAX System.

The LINDO computer package was selected to run the optimization program for this study since it is capable to handle a sufficiently large scale problem. In addition it could be run on the Purdue Vax 780 available in the Purdue Engineering Network which includes the School of Civil Engineering. The Purdue Vax which uses the Unix Operating

System developed at Berkeley has virtual memory and it can execute almost any program irrespective of the memory and processing unit requirements.

CHAPTER 7

APPLICATION OF THE OPTIMIZATION MODEL TO THE INTERSTATE HIGHWAY SYSTEM

Introduction

In this chapter the application of the optimization model to the interstate highway system of Indiana is described. This chapter is divided into four major parts. The first part explains the methodology adopted for selecting the pavement sections that entered into the optimization program at the beginning of the analysis period. The second part explains the methodology used for selecting additional pavement sections included in optimization program during the second through fifth year of the analysis period. The third part shows the results of applying the optimization model to the interstate highway system. The effect of different budget scenarios is also covered in this chapter. Finally, the graphical interactive technique is applied on a particular interstate route to visually verify the results obtained with the optimization routine.

Selection of Initial Pavement Contract Sections

The process of selecting pavement contract sections at the beginning of the analysis period, shown schematically in Figure 7.1, is summarized below.

1. Pavement sections were selected by contract section and categorized into two major types of pavements, namely asphalt (i.e. includes conventional pavements, full-depth, and overlayed pavements) and concrete (includes JRCP, CRCP, JPCP) pavements.

2. Asphalt pavement sections with a roughness number greater than 1400 counts per mile and concrete pavement sections with roughness numbers greater than 2000 counts per mile were identified and selected for the pavement condition survey.

3. Contract sections already identified as being rough were further divided into one-mile sections and the pavement condition rating was determined for each section using the rating procedure developed by IDOH for this purpose and explained in Chapter 4.

4. An average pavement condition rating was then computed for the entire contract section.

5. Other necessary performance data pertaining to these pavement sections were then obtained from the IDOH Research & Training Center. These include roughness number during the last four years, pavement age, pavement type, directional ADT, and contract length.

6. Performance factors which depend upon the above parameters were then computed. These include weighed directional ADT for each pavement section, change in roughness number between any two years, and cumulative ADT since the section in question was opened to traffic.

7. The equivalent performance curves described in Chapter 3 were then used to transform the afore-mentioned performance indicators into an equivalent scale from 0 to 100, 0 corresponds to very poor condition, and 100 corresponding to excellent condition.

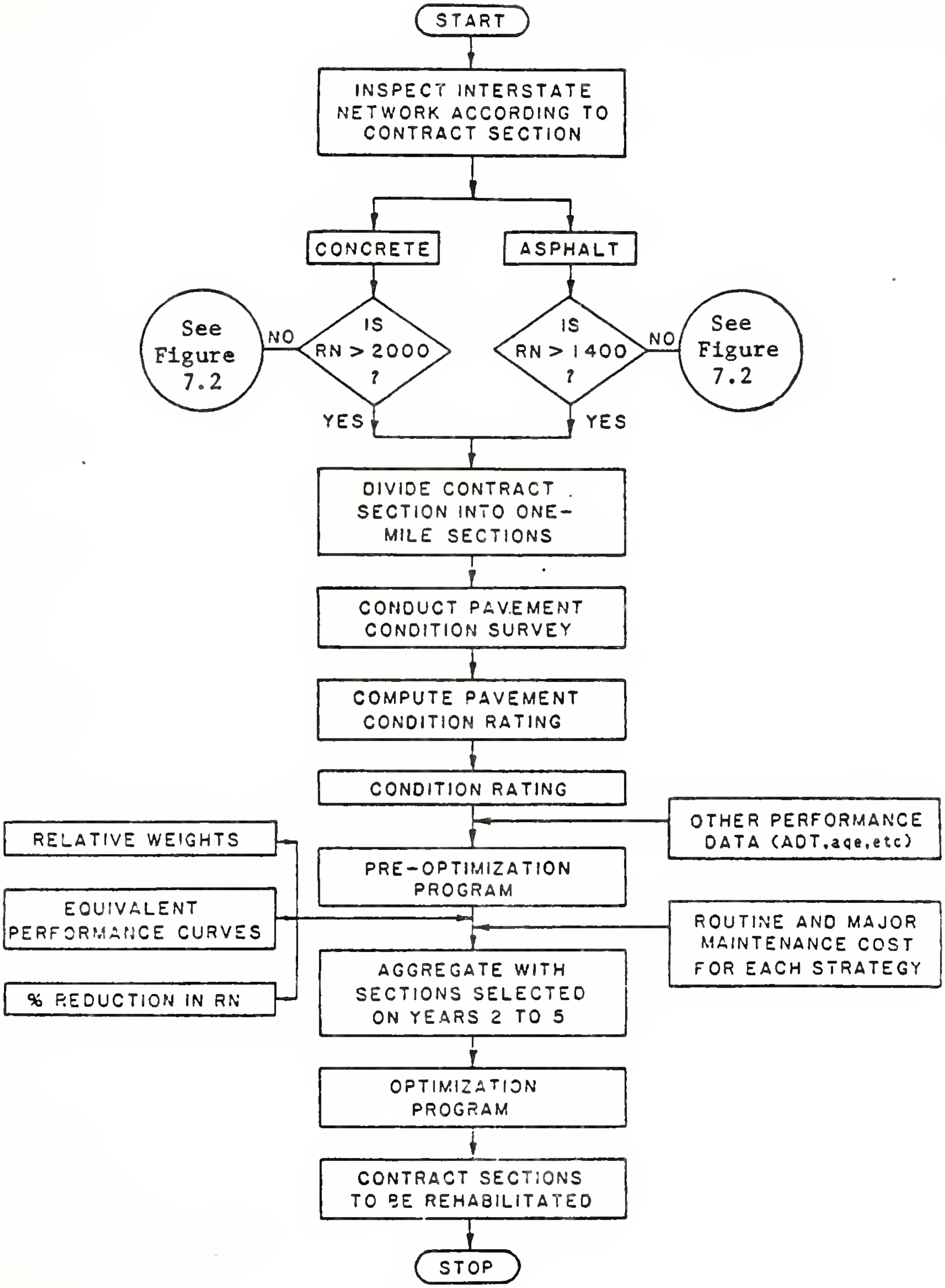


Figure 7.1 Steps Used for Selecting Initial Pavement Sections for the Optimization Model.

8. The performance factors were then weighed according to its relative importance among the factors being considered. The sum of the assigned weights should always be equal to one.

9. Resurfacing activities were then assigned to each contract section selected for the optimization problem based on the current ADT of the facility. A total of three resurfacing activities out of a possible seven were assigned to each pavement section.

10. Percent reduction in pavement roughness associated with the resurfacing activities assigned to each contract section were then computed using the procedure explained in Chapter 5.

11. Traffic growth factor associated with each pavement section was estimated and input to the optimization program.

12. Average routine maintenance costs expected during the next five years for the resurfacing strategies considered were input to the program.

13. Unit cost information associated with each resurfacing activity was then used along with the length of each contract section to compute the resurfacing costs of each pavement section considered in the formulation.

14. Budget estimates obtained from IDOH Planning Division for the current year as well as for the last four years were then used to estimate the expected budget for the next four years of the analysis period. This information was input to the optimization formulation.

15. The objective function and constraint coefficients were then computed using the equations described in Chapter 6.

16. The optimization program, based on a zero-one integer programming technique, was then used to run the proposed formulation as described in Chapter 6. The pavement contract sections selected for resurfacing by the optimization program during each year of the analysis period were then tabulated.

A total of 241 one-mile concrete pavement sections and five flexible pavement sections in the interstate system were observed to have roughness number exceeding the appropriate threshold values during the 1982 pavement condition survey.

Since the pavement condition survey was conducted at one-mile intervals, it was necessary to group the rating scores according to the contract section which is the unit of measurement used in the optimization formulation. Therefore the 241 one-mile pavement sections were finally grouped into seventy representative paving contract sections.

The five one-mile flexible pavement sections were not considered in the optimization analysis for the following reasons (see Table 7.1):

1. The two one-mile sections corresponding to contract no. 9589 were not contiguous and when compared with the roughness number obtained or the entire five mile section it barely exceeded the threshold value used (i.e. the average roughness number for the entire section was 1492 as compared to the threshold value of 1400).

2. A similar situation was found in contract no. 11664 in which the average roughness number for the entire section was actually below the threshold value used initially to screen the pavement sections (i.e. The average roughness number for the section was 1322 as compared to the threshold value of 1400).

3. The ages of the two contract sections were 8 and 5 years, respectively. This means that the two pavement sections were relatively new as compared to most of the concrete pavement sections entered into the optimization problem which are in the range of 20 years.

Table 7.1 Flexible Pavement Sections Rated During the 1982 Pavement Condition Survey Conducted in the Interstate Highway System

Route Number	Contract Number	Length (miles)	ADT	Pavement Type	Pavmt. Age	Roughness Number	PCI
I-65 S	RS-9589	1.0	11812	HAE III	7	2192	86
	RS-9589	1.0	15387	HAE III	7	1801	80
	RS-9589*	5.0	14128	HAE III	7	1491	83
I-69 S	RS-11664	1.0	7362	HAE IV	4	1424	88
	RS-11664	1.0	7362	HAE IV	4	1606	80
	RS-11664	1.0	7362	HAE IV	4	1914	80
	RS-11664*	5.7	7362	HAE IV	4	1322	83

* This information pertains to the entire pavement section and not to individual one-mile sections.

4. The average pavement condition index for these two contract sections was 83 which means that the overall structural condition of the pavement surface appeared to be in "good" condition.

5. Finally, the five one-mile sections were representative of only two contract sections which constituted less than three percent of the entire pavement network.

Considering 70 sections, 3 resurfacing strategies per section and 5 years in the analysis period, 1050 decision variables were initially required for the optimization model. A total of 1190 section constraints were included in the formulation. Since the primary purpose of developing the optimization model was to be used in a multi-year framework rather than on a yearly basis, there was a need to develop a procedure by which pavement sections that deteriorate within the next four years can be identified and analyzed. In the following paragraphs the methodology used for identifying deficient pavement sections in the next four years is described.

Selection of Additional Contract Sections

The procedure followed for selecting additional pavement sections to be considered after first year of the analysis period is shown schematically in Figure 7.2 and summarized below:

1. The roughness inventory data corresponding to years 1979 through 1982 were obtained from the IDOH Research and Training Center for each interstate route.

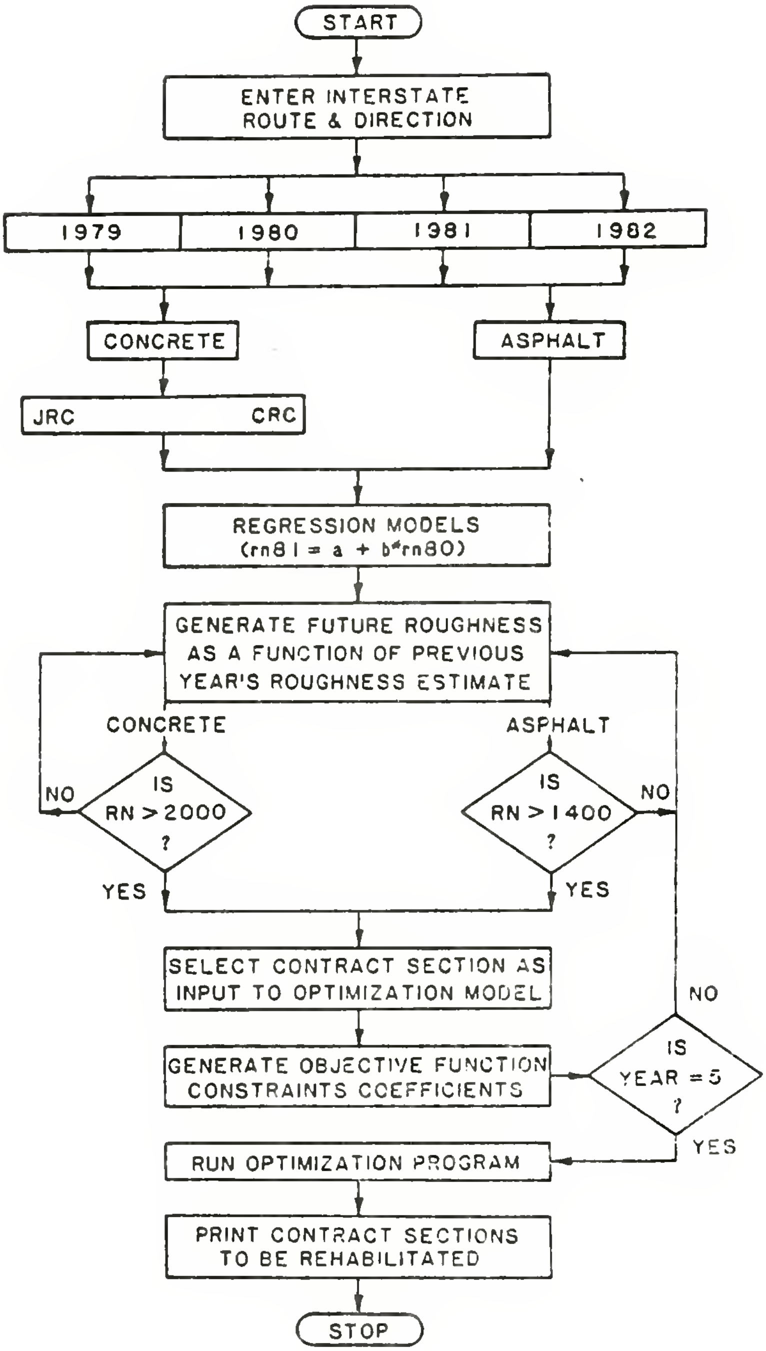


Figure 7.2 Steps Used for Selecting Additional Pavement Sections.

2. Summary tables containing performance information of the pavement section as well as the roughness numbers for the last four years were generated by interstate route and the information was tabulated by contract section. These include the length of the pavement section, pavement type and surface, directional ADT, pavement age, cumulative ADT, and the roughness numbers corresponding to the last four years.

3. All pavement sections which did not have roughness number measured in each of the the last four years were disregarded.

4. All pavement sections which were resurfaced within the last three years were also disregarded since it was assumed that any resurfacing performed in the interstate highway system, irrespective of the thickness of the surface course, will perform satisfactorily for at least during the five years considered in this analysis. This was based on the fact that the average interstate resurfacing in Indiana is about 8 years of age and the average roughness number is around 950 counts per mile.

5. Regression equations were then developed for each interstate route and pavement type combination using the roughness number measurements for two years, 1979 and 1981. The dependent variable was the 1981 roughness number with the 1979 roughness number as the independent variable. As an example of this regression, analysis for JRC pavements for Interstate 65 North is given in Figure 7.3. The regression models were assumed to be representative of the deterioration pavement sections were experiencing during that period of time. The regression models are summarized in Table 7.2. The equation to estimate roughness number for a particular year was developed as a function of the roughness number of the preceeding years by interpolating the results of the regression analysis given in Table 7.2.

6. The regression coefficients applicable to each interstate route and pavement type were then used to predict the roughness number for 1984, 1985, and so on.

7. All those pavement sections which exceeded the roughness limits associated with each type of pavement during any of these four years were then input to the optimization model in the year in which the roughness number was exceeded.

8. All other performance information associated with these pavement sections was then obtained in the same manner as explained at the beginning of this chapter. The only difference is that the parameter representing the

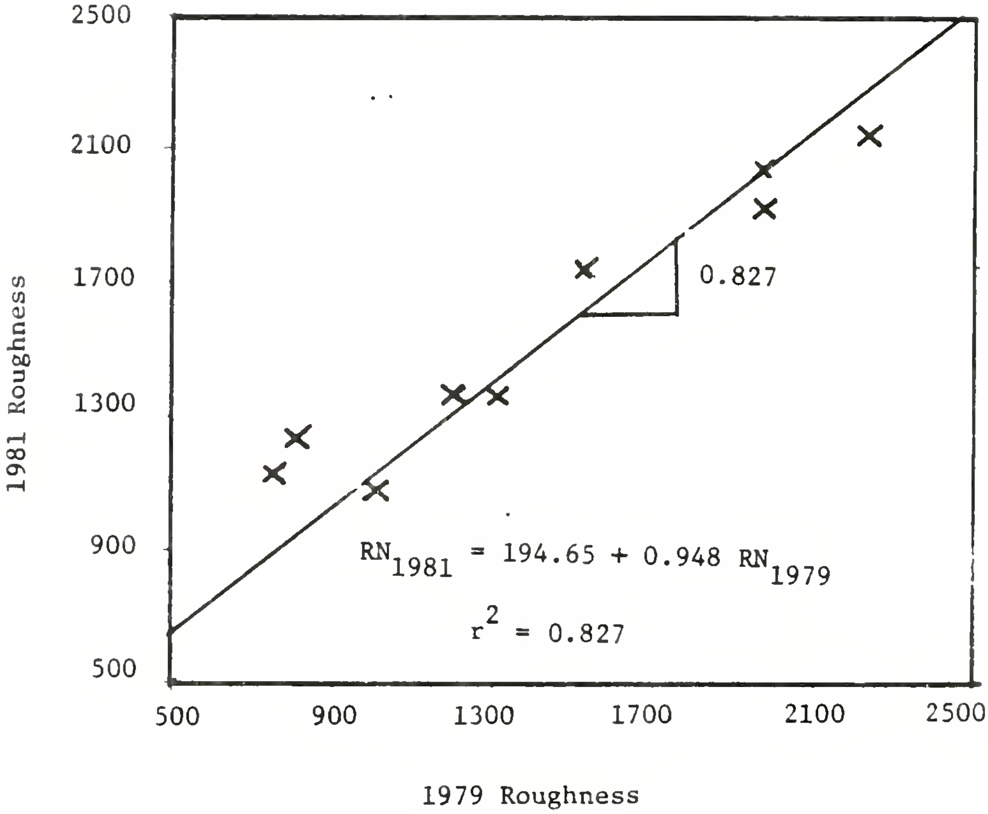


Figure 7.3 Regression Equation Results for Roughness Number Measured on JRC Pavements on Interstate 65 North (1979-1981).

Table 7.2 Regression Equations Developed for the Interstate Highway System

Route No.	Pavement Type	Regression Equation RN80 = a + b*(RN79)	Correlation Coefficient	Contracts Analyzed
I 64 E	JRC/PCC	RN80 = 231.68 + 0.907(RN79)	0.640	9
	Full Depth	RN80 = 316.30 + 0.755(RN79)	0.630	10
I 64 W	JRC/PCC	RN80 = 100.50 + 0.994(RN79)	0.837	9
	Full Depth	RN80 = 18.34 + 1.174(RN79)	0.766	10
I 65 N	CRC*	RN80 = 501.42 + 0.71(RN79)	0.701	18
	JRC**	RN80 = 194.65 + 0.948(RN79)	0.827	15
	OVERLAY*	RN80 = 398.89 + 0.714(RN79)	0.843	12
I 65 S	CRC	RN80 = 163.03 + 0.96(RN79)	0.823	18
	JRC	RN80 = 182.51 + 0.97(RN79)	0.946	13
	OVERLAY	RN80 = 398.89 + 0.714(RN79)	0.843	12
I 69 N	JRC	RN80 = 244.26 + 0.936(RN79)	0.678	25
I 69 S	JRC	RN80 = 244.26 + 0.936(RN79)	0.678	25
I 70 E	JRC	RN80 = 52.06 + 1.055(RN79)	0.643	19
I 70 W	JRC	RN80 = 182.33 + 0.96(RN79)	0.544	8
I 74 E	JRC	RN80 = 192.55 + 0.969(RN79)	0.781	20
I 74 W	JRC	RN80 = 191.37 + 0.908(RN79)	0.867	21

* The regression models developed for CRC pavements and overlay pavements for Interstate 65 North were used to generate the future roughness numbers for CRC and overlay pavements located on other interstate routes since there were not enough observations on these routes to generate reliable prediction models.

** The models developed for jointed reinforced concrete pavements for Interstate 65 North were used to generate the future roughness numbers for Interstate 94 and Interstate 465 since there were not enough observations to generate reliable models for these routes.

pavement condition index was eliminated from the formulation since pavement condition survey was initiated only in 1982 as explained in Chapter 4.

Development of Regression Equations

The primary reason for developing separate regression models for each interstate route is to take into account indirectly the age of the pavement as well as the traffic distribution of the route in question. For example, the regression model for Interstate 64 East for full-depth asphalt pavements comprises all contract sections which have an ADT between 3,000 and 5,000 vehicles per day and average pavement age of 7 years as compared to the contiguous concrete pavement sections which have an average pavement age of 16 and 12 years, respectively (see Figures 7.4 and 7.5). The regression models for Interstate 65 North, on the other hand, represents pavement sections which are between 2 and 9 years old for asphalt pavements, and between 13 and 24 years old for jointed reinforced and continuously reinforced concrete pavements. The ADT is also much higher as compared to I-64 East, between 8,000 and 35,000 vehicles per day (see Figures 7.6 and 7.7). Furthermore, there is a higher truck distribution on Interstate 65 North rather than on Interstate 64 East. Therefore, it can be expected that the rate of deterioration is more critical (on the average) on Interstate 65 North as compared to Interstate 64 East.

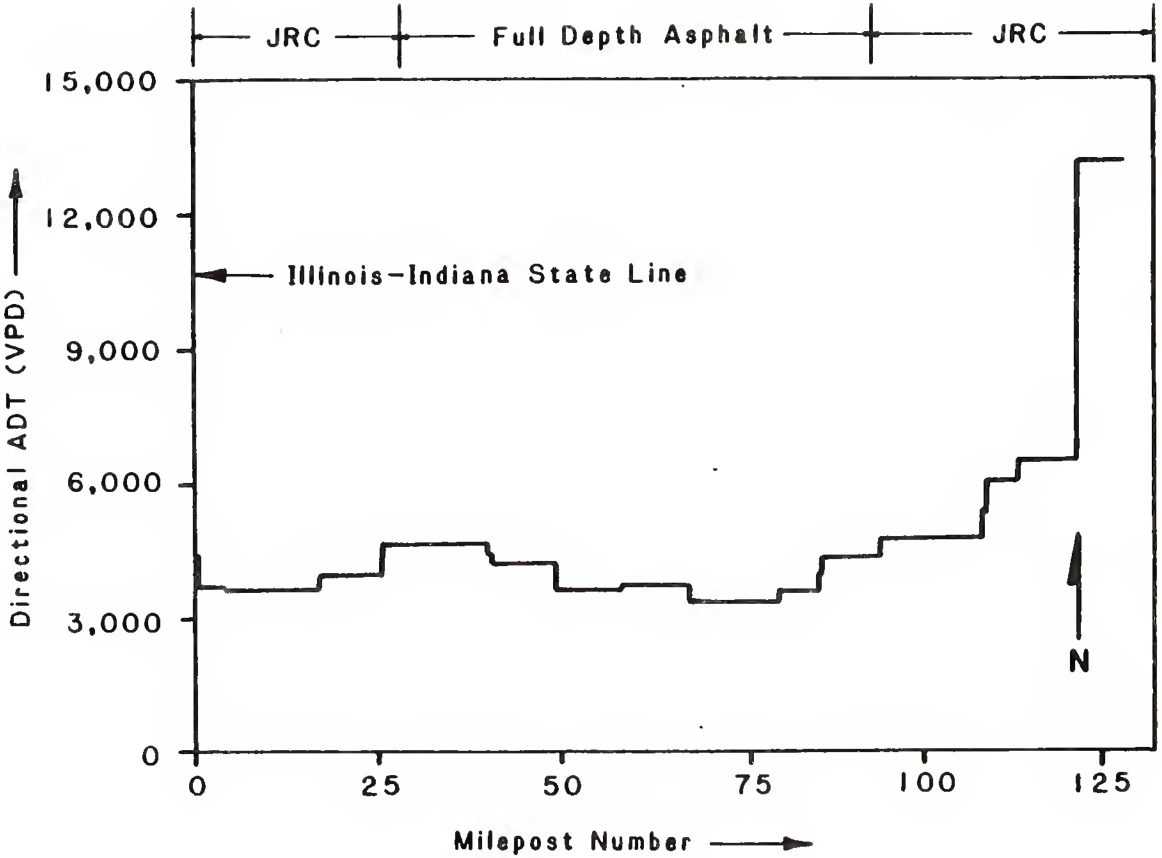


Figure 7.4 Directional ADT Distribution for Interstate 64 East During 1982.

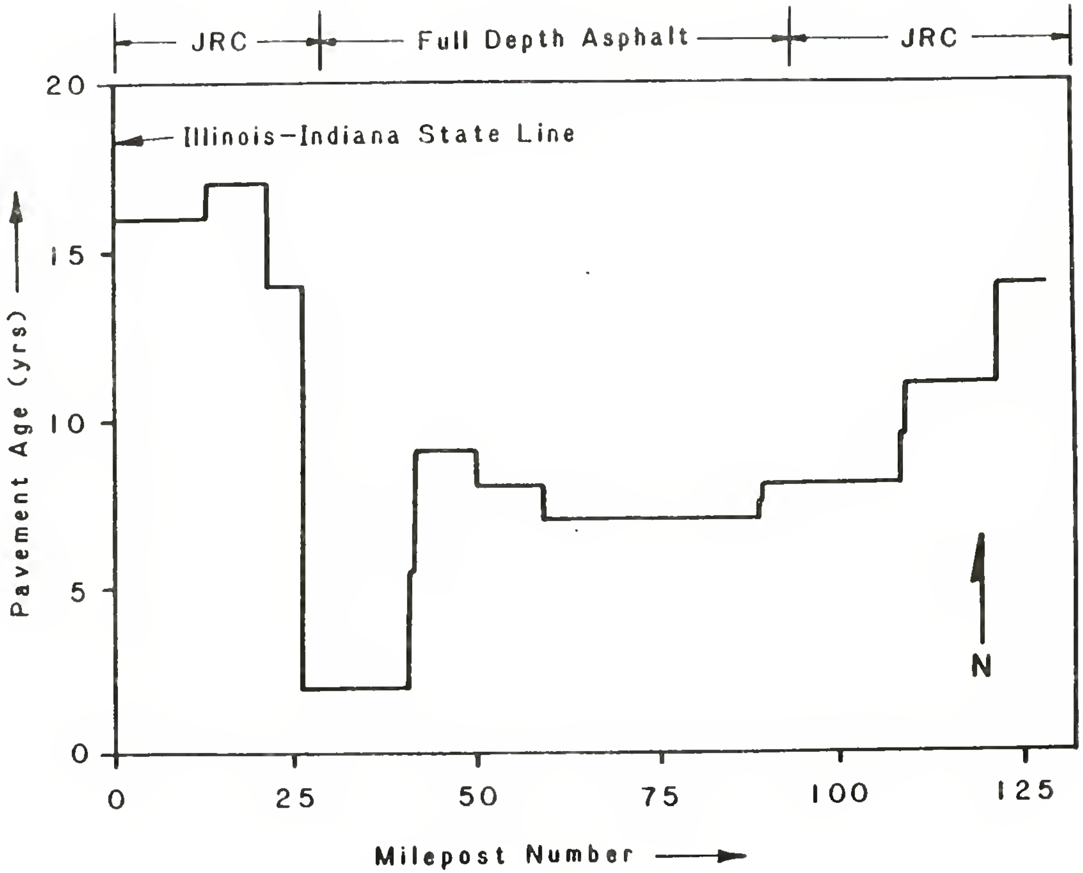


Figure 7.5 Pavement Age Distribution for Interstate 64 East During 1982.

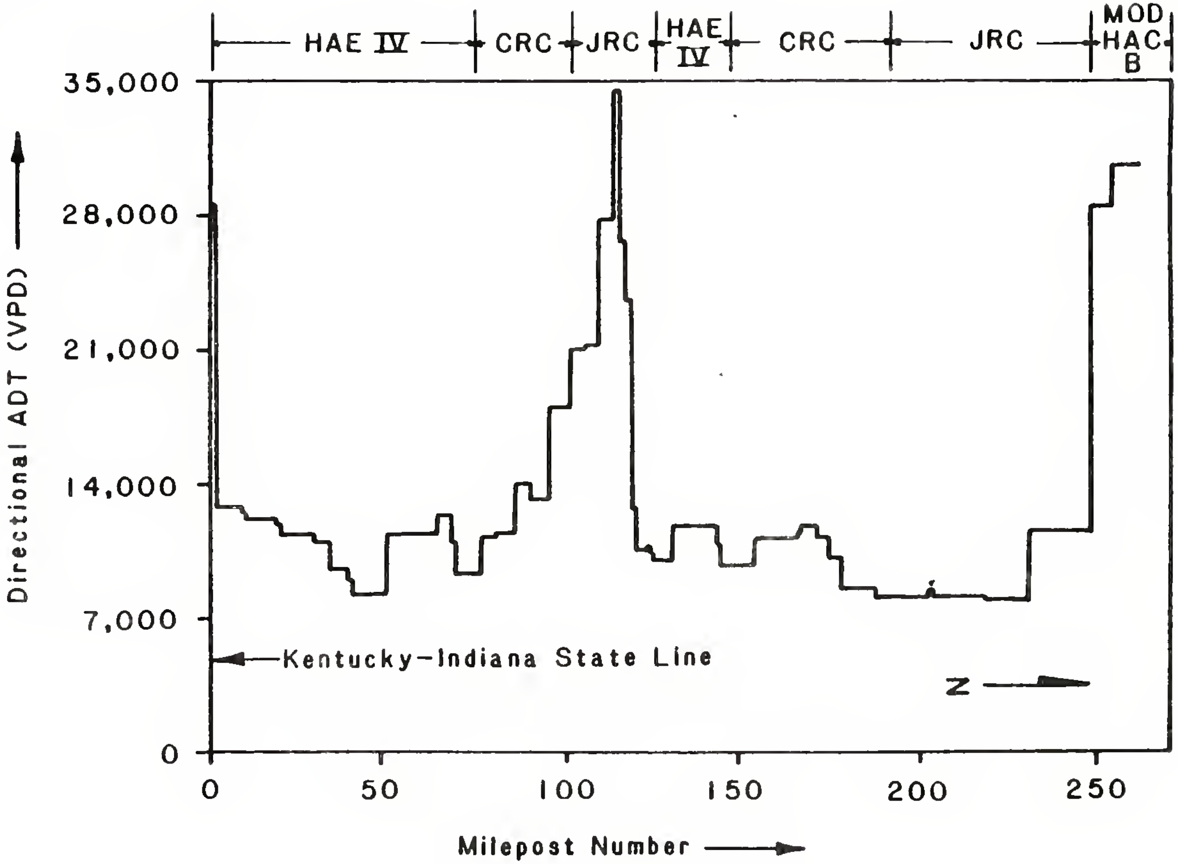


Figure 7.6 Directional ADT Distribution for Interstate 65 North During 1982.

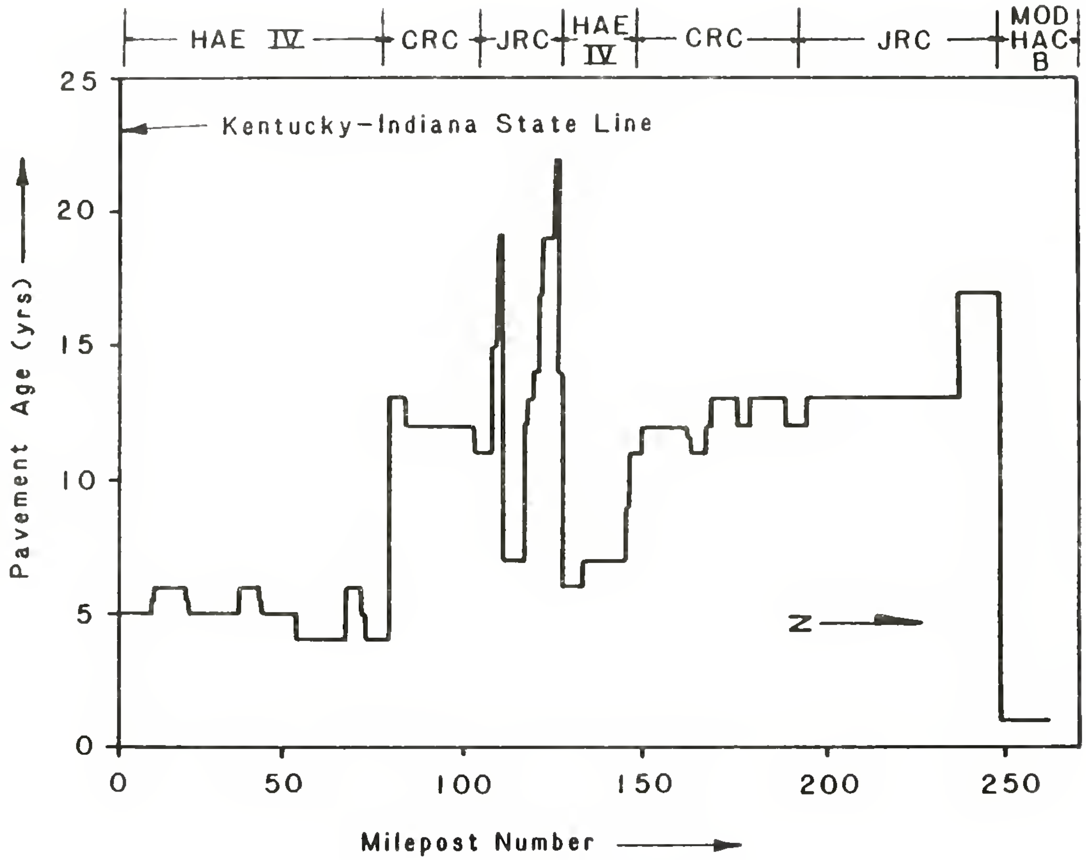


Figure 7.7 Pavement Age Distribution for Interstate 65 North During 1982.

Climatic Considerations

To take into account the effect of climate in the modelling process, the state of Indiana was divided into two climatic zones as shown in Figure 7.8. Previous study conducted at Purdue University in the area of pavement evaluation divided the State into three regional zones using the AASHTO regional factors [71] . However, the primary reason for including the regional zones in this study was to recognize the difference in climate experienced by Interstate 65 which is the only interstate route crossing the State from north to south, and for this purpose the consideration of only two zones was adequate. Consequently, separate regression models were developed for the northern and southern parts of Interstate 65.

Summary of Results-Regression Equations

The roughness number generated for the interstate highway system using the afore-mentioned procedure for years 1983 through 1987 as well as the roughness number corresponding to years 1979 through 1983 are summarized in Tables B.1 through B.14 in Appendix B according to pavement type and interstate route. The pavement sections that were selected as input to the optimization model are marked in these Tables with an asterisk (*) next to the roughness

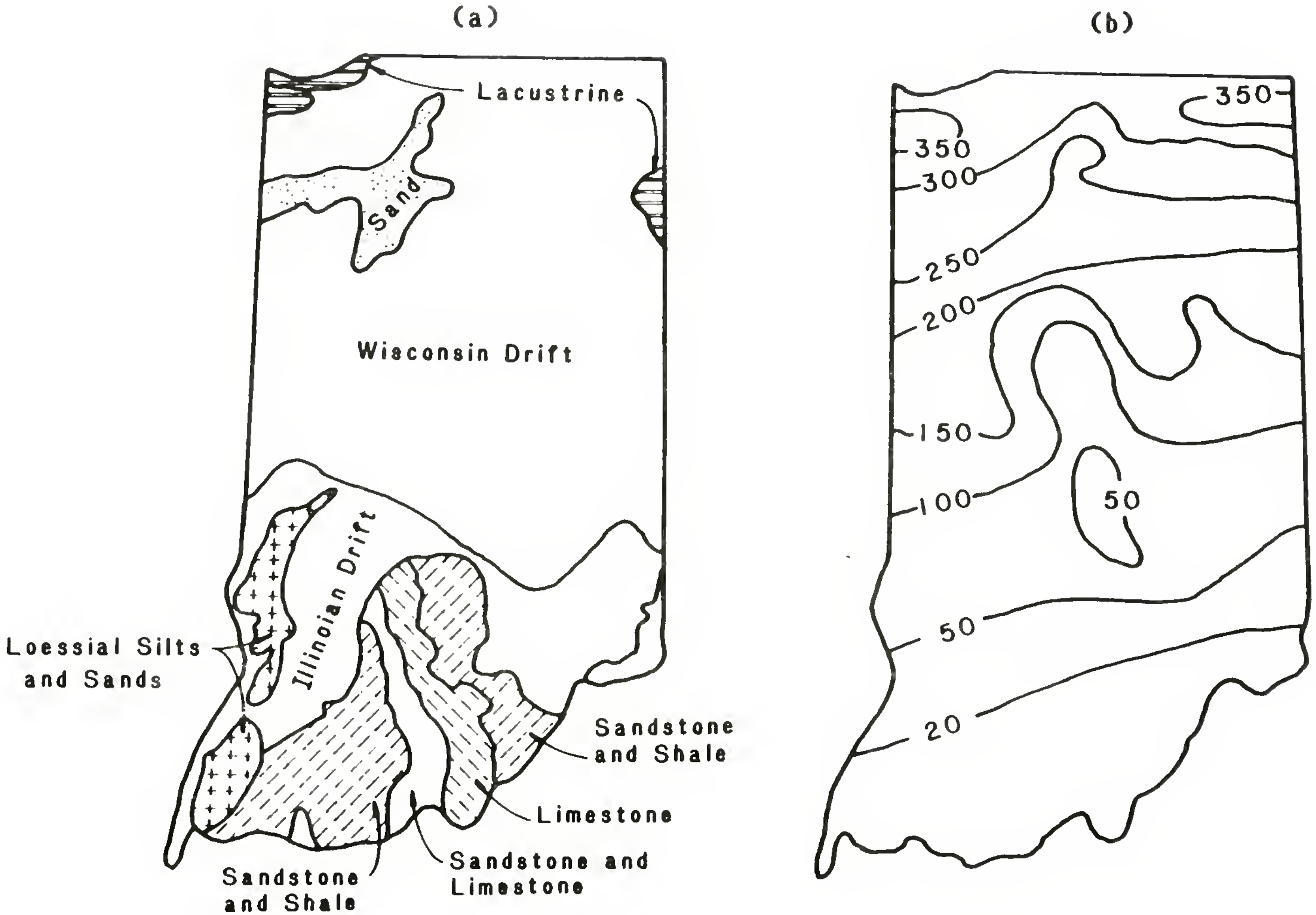
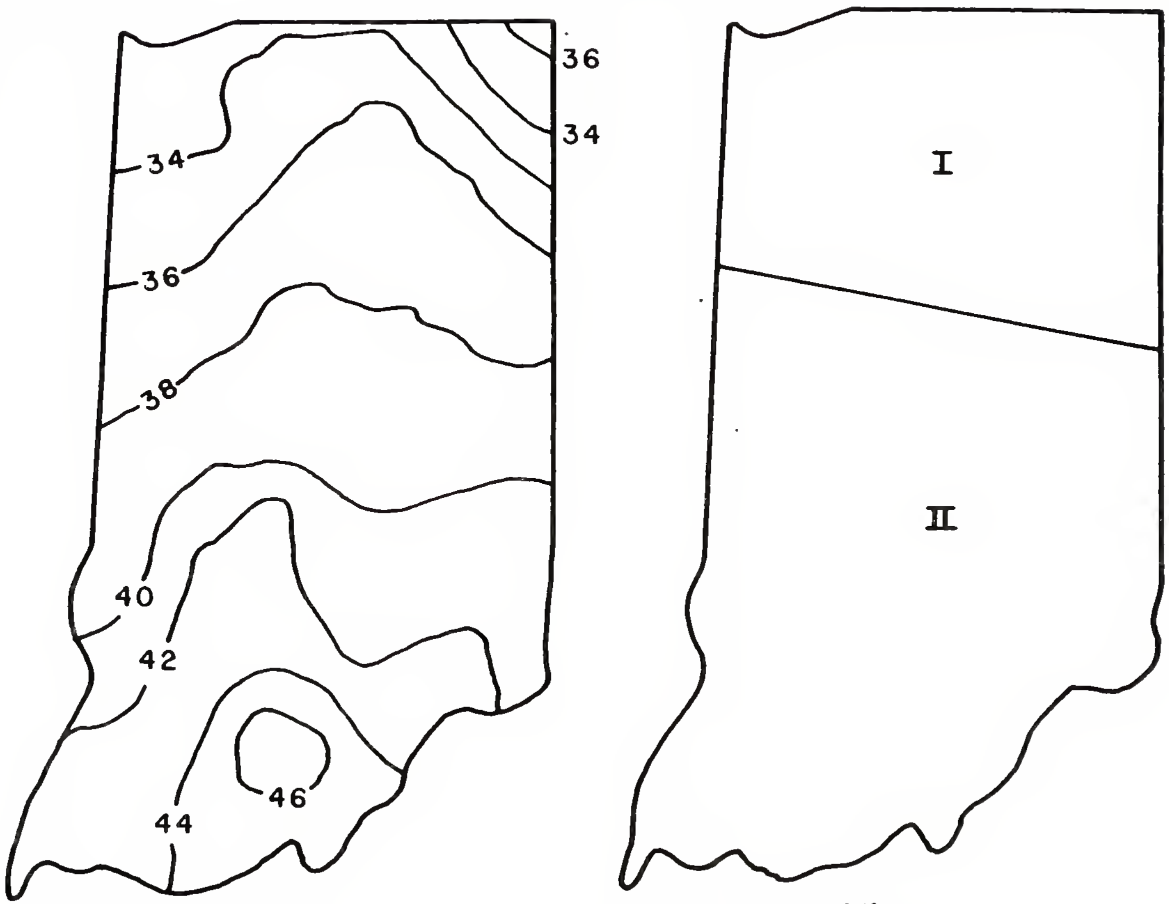


Figure 7.8 Distribution of Climatic and Soils Characteristics in Indiana: (a) Distribution of Soils and Rocks, (b) Mean Freezing Index Distribution. [69]



(c) (d)

Figure 7.8 Distribution of Climatic and Soils Characteristics in Indiana: (c) Mean Rainfall Distribution, (d) Regional Zones Adopted . [69] (Continued).

number used for selecting them. For example, Table B.5 shows the contract sections corresponding to Interstate 69 north-bound lane which have four years of roughness data available. For this particular route, contract section 7199 was selected as input to the optimization model at the start of year 1984 with a roughness number of 2040 counts per mile, whereas contract section 5995 was entered to the model at the beginning of year 1985 with a roughness number of 2006 counts per mile. Also contract section 6022 was input to the optimization model at the start of year 1986 with a roughness number of 2090 counts per mile. Other data pertaining to these pavement sections such as contract length, type of surface, directional ADT, pavement age, and cumulative ADT since the last time a major improvement was performed on the section, are also summarized in these Tables in columns 2 through 6, respectively. All of these data are used to generate the coefficients of the objective function and constraints defined in Chapter 6.

In summary, forty-eight additional pavement contract sections were incorporated into the optimization problem, representing 190.1 miles or about 20 percent of the interstate pavement network. In other words, the proposed procedure estimates that at least 20 percent of the interstate network of Indiana will need resurfacing within the next

five years assuming roughness numbers correctly represent pavement surface condition.

Operation of the Optimization Model

The pavement sections identified as deficient either at the first year or during subsequent years in the analysis period are then used as input to the optimization problem. The optimization model developed for the interstate highway system is a zero-one integer programming problem based on the branch and bound technique described in Chapter 6. The unit of measurement considered in this study is the contract section. The information pertaining to the contract sections selected at the start of the analysis period is summarized in Table 7.3. The information pertaining to the additional sections selected is summarized in Table 7.4. The year in which the pavement sections are incorporated into the optimization problem is also indicated in these Tables. Also shown in these Tables are the feasible resurfacing strategies applicable to the input sections.

Application of the Model

To illustrate the application of the multi-year optimization model, the interstate highway system was used. A total of seventy contract sections was initially selected and an additional forty-eight for subsequent years using the

Table 7.3 Information Pertaining to the Initial Pavement Sections Selected as Input to the Model

Route Number	Contract Number	Length miles	Surface Type*	ADT vpd	Age	RN Used	Year Input	Resurfacing Activity** a	b	c	d	e	f	g
I-65 n	8001	4.6	253	13225.	11.	2424.	1982	0	0	1	1	1	0	0
I-74 e	5481	5.8	252	6450.	19.	2216.	1982	1	1	1	0	0	0	0
I-265 s	10033	7.1	252	5600.	6.	2777.	1982	1	1	1	0	0	0	0
I-69 n	6141	3.7	252	7362.	17.	3137.	1982	1	1	1	0	0	0	0
I-69 n	6183	6.1	252	6600.	17.	2589.	1982	1	1	1	0	0	0	0
I-69 n	6415	6.4	252	6100.	17.	2420.	1982	1	1	1	0	0	0	0
I-69 n	6063	5.1	252	10025.	18.	2483.	1982	0	0	1	1	1	0	0
I-69 n	6142	6.0	252	7150.	17.	2079.	1982	1	1	1	0	0	0	0
I-69 n	6022	3.7	252	7150.	18.	2055.	1982	1	1	1	0	0	0	0
I-69 n	5995	4.1	252	7150.	19.	2031.	1982	1	1	1	0	0	0	0
I-69 n	6505	4.4	252	6500.	18.	2480.	1982	1	1	1	0	0	0	0
I-69 n	6930	3.6	252	5436.	16.	2069.	1982	1	1	1	0	0	0	0
I-69 s	6506	4.4	252	6500.	18.	2218.	1982	1	1	1	0	0	0	0
I-69 s	6022	3.7	252	7150.	18.	2245.	1982	1	1	1	0	0	0	0
I-69 s	6063	5.1	252	8012.	18.	2231.	1982	1	1	1	0	0	0	0
I-69 s	6415	6.4	252	6100.	17.	2322.	1982	1	1	1	0	0	0	0
I-69 s	6183	6.1	252	6600.	17.	2527.	1982	1	1	1	0	0	0	0
I-69 s	6141	3.7	252	7362.	17.	2348.	1982	1	1	1	0	0	0	0
I-65 s	6539	4.5	252	11500.	16.	2002.	1982	0	0	1	1	1	0	0
I-65 s	7275	2.9	252	8100.	14.	2669.	1982	1	1	1	0	0	0	0
I-65 s	7143	6.2	252	8100.	14.	2430.	1982	1	1	1	0	0	0	0
I-65 s	7935	7.8	253	9837.	11.	2577.	1982	1	1	1	0	0	0	0
I-65 s	7858	5.3	253	11187.	10.	2972.	1982	0	0	1	1	1	0	0
I-65 s	8232	4.1	253	9887.	10.	2031.	1982	1	1	1	0	0	0	0
I-65 s	8208	5.7	253	9837.	11.	2057.	1982	1	1	1	0	0	0	0
I-65 s	7633	5.2	253	8560.	12.	2063.	1982	1	1	1	0	0	0	0
I-65 s	7677	4.4	253	8560.	12.	2189.	1982	1	1	1	0	0	0	0
I-65 s	7714	5.5	253	8125.	12.	2153.	1982	1	1	1	0	0	0	0
I-65 s	7677	4.4	253	8560.	12.	2294.	1982	1	1	1	0	0	0	0
I-70 e	7092	5.8	252	12250.	14.	2640.	1982	0	0	1	1	1	0	0
I-70 w	7057	2.0	252	12250.	14.	2401.	1982	0	0	1	1	1	0	0
I-70 e	7389	4.8	252	12500.	12.	2185.	1982	0	0	1	1	1	0	0
I-70 e	6968	7.3	252	17500.	14.	2248.	1982	0	0	1	1	1	0	0
I-70 w	7091	0.7	252	12000.	13.	2626.	1982	0	0	1	1	1	0	0
I-70 e	7390	6.6	252	12500.	12.	2106.	1982	0	0	1	1	1	0	0

*The code for type of surface or pavement is :
1. Jointed Reinforced Concrete (JRC) = 252
2. Continuouley Reinforced Concrete (CRC) = 253, 263

**The resurfacing strategy code is shown in Table 7.5

Table 7.3 Information Pertaining to the Initial Pavement Sections Selected as Input to the Model (Continued)

Route Number	Contract Number	Length miles	Surface Type*	ADT vpd	Age	RN Used	Year Input	Resurfacing Activity** a	b	c	d	e	f	g
I-74 e	4843	3.5	252	8000.	21.	2240.	1982	1	1	1	0	0	0	0
I-74 e	6269	5.3	252	3763.	14.	2258.	1982	1	1	1	0	0	0	0
I-74 e	4545	6.6	252	11450.	21.	2345.	1982	0	0	1	1	1	0	0
I-74 e	5434	2.7	252	5550.	19.	2218.	1982	1	1	1	0	0	0	0
I-74 e	4507	5.8	252	9025.	22.	2055.	1982	1	1	1	0	0	0	0
I-74 w	5434	2.7	252	5550.	21.	2048.	1982	1	1	1	0	0	0	0
I-65 n	5856	3.2	252	10650.	18.	2484.	1982	0	0	1	1	1	0	0
I-69 n	7274	5.8	252	12150.	13.	2863.	1982	0	0	1	1	1	0	0
I-69 n	5968	4.0	252	11600.	18.	2209.	1982	0	0	1	1	1	0	0
I-69 n	5805	4.4	252	11309.	19.	2464.	1982	0	0	1	1	1	0	0
I-69 n	5842	2.2	252	9525.	19.	2078.	1982	1	1	1	0	0	0	0
I-69 n	5814	3.7	252	9525.	18.	2382.	1982	1	1	1	0	0	0	0
I-69 n	5843	2.7	252	9525.	17.	2568.	1982	1	1	1	0	0	0	0
I-69 n	5857	5.3	252	7312.	19.	2686.	1982	1	1	1	0	0	0	0
I-69 n	6062	3.1	252	7312.	18.	2533.	1982	1	1	1	0	0	0	0
I-69 s	5857	5.3	252	7312.	19.	2641.	1982	1	1	1	0	0	0	0
I-69 s	5814	4.2	252	9525.	18.	2479.	1982	1	1	1	0	0	0	0
I-69 s	5842	1.7	252	9525.	18.	2433.	1982	1	1	1	0	0	0	0
I-69 s	5805	4.4	252	11582.	19.	2442.	1982	0	0	1	1	1	0	0
I-69 s	5968	4.0	252	11036.	18.	2008.	1982	0	0	1	1	1	0	0
I-69 s	7274	5.8	252	12150.	13.	2750.	1982	0	0	1	1	1	0	0
I-70 e	7473	4.5	252	25500.	13.	2487.	1982	0	0	1	1	1	0	0
I-70 e	7338	6.4	252	12888.	13.	3495.	1982	0	0	1	1	1	0	0
I-70 e	6685	5.3	252	12888.	14.	2554.	1982	0	0	1	1	1	0	0
I-70 e	6602	9.2	252	9412.	14.	3159.	1982	1	1	1	0	0	0	0
I-70 e	6603	6.4	252	9287.	14.	2965.	1982	1	1	1	0	0	0	0
I-70 e	6815	6.9	252	9287.	15.	3491.	1982	1	1	1	0	0	0	0
I-70 w	6603	6.4	252	9287.	15.	2713.	1982	1	1	1	0	0	0	0
I-70 w	6826	0.4	252	9412.	14.	2599.	1982	1	1	1	0	0	0	0
I-70 w	6602	9.2	252	9412.	14.	2787.	1982	1	1	1	0	0	0	0
I-70 w	6685	5.3	252	9412.	14.	2647.	1982	1	1	1	0	0	0	0
I-70 w	7338	6.4	252	12888.	14.	3078.	1982	0	0	1	1	1	0	0
I-70 w	7473	4.5	252	16300.	13.	2424.	1982	0	0	1	1	1	0	0
I-70 w	10348	2.5	252	45000.	6.	2235.	1982	0	0	0	0	1	1	1
I-70 w	6956	3.7	252	20500.	15.	2162.	1982	0	0	1	1	1	0	0

*The code for surface type or pavement is:
1. Jointed Reinforced Concrete (JRC) = 252
2. Continuously Reinforced Concrete (CRC) = 253,263

**The resurfacing activity code is shown in Table 7.5

Table 7.4 Information Pertaining to the Additional Pavement Sections Selected as Input to the Model

Route Number	Contract Number	Length miles	Surface Type*	ADT vpd	Age	RN Used	Year Input	Maintenace Activity** a	b	c	d	e	f	g
1-65 n	10232	1.6	261	27267	7	2059	1986	0	0	1	1	1	0	0
1-65 n	5856	3.2	252	12686	19	2088	1983	0	0	1	1	1	0	0
1-65 s	10347	1.2	261	27675	7	2060	1985	0	0	1	1	1	0	0
1-65 s	7714	5.5	253	8139	13	2052	1986	1	1	1	0	0	0	0
1-65 s	7677	4.4	253	9543	13	2071	1984	1	1	1	0	0	0	0
1-65 s	7633	5.2	253	8560	13	2027	1985	1	1	1	0	0	0	0
1-65 s	7624	1.7	253	23821	13	2029	1986	0	0	1	1	1	0	0
1-65 s	7198	3.3	252	8100	15	2051	1986	1	1	1	0	0	0	0
1-65 s	6333	1.4	252	15843	17	2003	1985	0	0	1	1	1	0	0
1-65 s	5969	2.5	252	20256	19	2077	1984	0	0	1	1	1	0	0
1-65 s	4710	1.4	252	10700	22	2077	1986	0	0	1	1	1	0	0
1-69 n	7199	5.4	252	11450	13	2040	1984	0	0	1	1	1	0	0
1-69 n	6930	3.6	252	5448	17	2012	1984	1	1	1	0	0	0	0
1-69 n	6063	5.1	252	8088	19	2027	1984	1	1	1	0	0	0	0
1-69 n	6022	3.7	252	7150	19	2091	1986	1	1	1	0	0	0	0
1-69 n	5995	4.1	252	7102	20	2006	1985	1	1	1	0	0	0	0
1-69 n	5968	4.0	252	11149	19	2101	1984	0	0	1	1	1	0	0
1-69 n	5805	4.4	252	11499	20	2039	1985	0	0	1	1	1	0	0
1-69 s	6930	3.6	252	5448	17	2099	1986	1	1	1	0	0	·0	0
1-69 s	6022	3.7	252	7150	19	2053	1984	1	1	1	0	0	0	0
1-69 s	5995	4.1	252	7102	20	2089	1986	1	1	1	0	0	0	0
1-69 s	5968	4.0	252	11149	19	2080	1984	0	0	1	1	1	0	0

*The code for type of surface or pavement is:
1. Jointed Reinforced Concrete (JRC) = 252
2. Continuously Reinforced Concrete (CRC) = 253, 263

**The resurfacing strategy code is shown in Table 7.5

Table 7.4 Information Pertaining to the Additional Pavement Sections Selected as Input to the Model (Continued)

Route Number	Contract Number	Length miles	Surface Type*	ADT vpd	Age	RN Used	Year Input	Resurfacing Strategy** a	b	c	d	e	f	g
i-70 e	7390	6.6	252	12462	13	2125	1983	0	0	1	1	1	0	0
i-70 e	7092	5.8	252	12250	15	2126	1985	0	0	1	1	1	0	0
i-70 e	7091	0.7	252	12000	14	2135	1983	0	0	1	1	1	0	0
i-70 e	6968	7.3	252	17140	15	2032	1983	0	0	1	1	1	0	0
i-70 e	6956	3.7	252	20500	16	2015	1986	0	0	1	1	1	0	0
i-70 w	7390	6.6	252	12462	13	2072	1986	0	0	1	1	1	0	0
i-70 w	7389	4.8	252	12500	13	2001	1985	0	0	1	1	1	0	0
i-70 w	7091	0.7	252	12000	14	2025	1986	0	0	1	1	1	0	0
i-70 w	6968	7.3	252	17140	15	2068	1986	0	0	1	1	1	0	0
i-70 w	6956	3.7	252	20500	16	2072	1986	0	0	1	1	1	0	0
i-74 e	6290	6.3	252	3763	18	2071	1986	1	1	1	0	0	0	0
i-74 e	6269	5.3	252	3855	15	2118	1985	1	1	1	0	0	0	0
i-74 e	6064	6.0	252	5212	19	2021	1986	1	1	1	0	0	0	0
i-74 e	5481	5.8	252	6450	20	2012	1984	1	1	1	0	0	0	0
i-74 e	5434	5.4	252	6008	20	2052	1983	1	1	1	0	0	0	0
i-74 e	4843	3.5	252	8000	22	2067	1983	1	1	1	0	0	0	0
i-74 e	4614	7.5	252	5907	22	2089	1985	1	1	1	0	0	0	0
i-74 e	4507	5.8	252	8320	23	2019	1984	1	1	1	0	0	0	0
i-465 i	5046	2.5	252	36458	21	2032	1986	0	0	0	0	1	1	1
i-465 i	4710	3.2	252	23889	22	2024	1986	0	0	1	1	1	0	0
i-465 o	5969	1.3	252	23331	19	2027	1985	0	0	1	1	1	0	0
i-465 o	5483	2.9	252	24110	20	2036	1984	0	0	1	1	1	0	0
i-465 o	5046	2.5	252	36526	21	2026	1985	0	0	0	0	1	1	1
i-465 o	4710	3.4	252	21900	22	2029	1985	0	0	1	1	1	0	0
i-465 o	4709	1.2	252	38117	22	2023	1984	0	0	0	0	1	1	1

*The code for type of surface or pavement is:
1. Jointed Reinforced Concrete (JRC) = 252
2. Continuously Reinforced Concrete (CRC) = 253, 263

**The resurfacing strategy code is shown in Table 7.5.

regression equations developed for each interstate route and pavement type. Only those pavement sections exceeding 2000 counts per mile during 1982 were considered as input to the optimization problem.

Table 7.5 shows the ADT values used to assign the resurfacing strategies to the contract sections selected for the optimization problem. The number "1" in the matrix implies that a particular resurfacing activity can be assigned to the pavement section being considered if the current ADT is within the range shown in the Table. For the purpose of this study the annual traffic growth factor was assumed to be 4%.

Table 7.6 contains the percent reduction in pavement distress, initial resurfacing cost, and annual pavement routine maintenance cost associated with each feasible resurfacing strategy considered in this study. Table 7.7 contains the input parameters for the optimization model. Table 7.8 shows the relative weights assigned to the performance factors considered in the model for the first year as well as those used for pavement sections entered in years 2 through 5 of the analysis period.

Table 7.9 contains the budget scenarios as well as the present worth of budget considered in this study. An

Table 7.7 Input Parameters for Interstate System Optimization Model

	Calendar Year					
Parameter	1982	1983	1984	1985	1986	Total
Contract Sections	70	6	12	13	17	118
Analysis Year	1	2	3	4	5	---
Decision Variables	1050	72	108	78	51	1359
Section Constraints	1190	78	108	65	17	1458
Budget Constraints	1	1	1	1	1	5

Table 7.8 Relative Weights Assigned to Performance Indicators - Interstate Formulation

Performance Indicator	Relative Weights Assigned	
	1st Year	2nd-5th Year
Roughness	0.40	0.50
Pavement Age	0.10	0.15
Pavement Condition	0.30	----
Change in Roughness	0.20	0.35

Table 7.9 Budget Scenarios and Present Worth of Budget Considered in this Study

Calendar Year	Budget Scenarios, (in $ millions)				
	1	2 *	3	4	5
1982	17.0	17.0	17.0	17.0	17.0
1983	35.2	32.0	28.8	24.0	19.2
1984	50.6	46.0	41.4	34.5	27.6
1985	66.0	60.0	54.0	45.0	36.0
1986	82.5	75.0	67.5	56.3	45.0
Total Budget	251.3	230.0	208.7	176.8	144.8
Present Worth	203.8	186.7	169.6	144.1	118.4
% Normal Budget	1.1	1.0	0.9	0.75	0.6

Note: * - indicates normal level of budget

interest rate of 6 percent was used to compute the present worth of budget.

Discussion of Results

Optimal Resurfacing Program

Table 7.10 presents the results of the application of the contract section worth optimization model by summarizing the pavement contract sections that were selected for resurfacing under budget scenario 2. Results under other budget scenarios are included in Appendix D. The symbol '*' indicates the calendar year in which a particular resurfacing strategy is to be applied at each pavement contract section. For example, contract section #1 was selected by the optimization program to be resurfaced during calendar year 1984. The resurfacing strategy 'e', which corresponds to a 3" overlay, was assigned to this pavement section. The total project cost associated with this pavement section using this resurfacing strategy was computed as follows:

$$TPRC = \frac{\$412,000}{CLM} * 4.6CLM * (1.06)^3 = \$2,257,214$$

where:

TPRC = total project resurfacing cost for the entire contract section;

CLM = center-line miles of the section.

Table 7.10 Results from Contract Section Worth Model for Budget Scenario 2: Interstate Highway System

Section (coded)	Calendar Year 1982	1983	1984	1985	1986	Resurfacing Activity +	Section Length
1			*			e	4.6
2						n/s	5.8
3						n/s	7.1
4			*			c	3.7
5				*		c	6.1
6					*	c	6.4
7		*				e	5.1
8				*		c	6.0
9			*			c	3.7
10			*			c	4.1
11			*			c	4.4
12						n/s	3.6
13			*			c	4.4
14		*				c	3.7
15				*		c	5.1
16			*			c	6.4
17					*	c	6.1
18			*			c	3.7
19	*					e	4.5
20		*				c	2.9
21		*				c	6.2
22				*		c	7.8
23		*				e	5.3
24				*		c	4.1

Table 7.10 Results from Contract Section Worth Model for Budget Scenario 2: Interstate Highway System (Continued)

Section (coded)	Calendar Year 1982	1983	1984	1985	1986	Resurfacing Activity †	Section Length
25					*	c	5.7
26						n/s	5.2
27					*	a	4.4
28					*	a	5.5
29					*	c	4.4
30		*				e	5.8
31	*					e	2.0
32						n/s	4.8
33			*			e	7.3
34	*					e	0.7
35					*	a	6.6
36	*					c	3.5
37						n/s	5.3
38			*			a	6.6
39			*			c	2.7
40				*		c	5.8
41			*			c	2.7
42	*					e	3.2
43				*		e	5.8
44			*			e	4.0
45			*			a	4.4
46	*					c	2.2
47		*				c	3.7
48	*					c	2.7

Table 7.10 Results from Contract Section Worth Model for Budget Scenario 2: Interstate Highway System (Continued)

Section (coded)	Calendar Year 1982	1983	1984	1985	1986	Resurfacing Activity+	Section Length
49				*		c	5.3
50				*		c	3.1
51			*			c	5.3
52					*	c	4.2
53		*				c	1.7
54	*					e	4.4
55					*	e	4.0
56				*		e	5.8
57	*					e	4.5
58		*				e	6.4
59		*				e	5.3
60				*		c	9.2
61			*			c	6.4
62		*				c	6.9
63				*		c	6.4
64	*					c	0.4
65						n/s	9.2
66		*				c	5.3
67		*				e	6.4
68	*					e	4.5
69	*					g	2.5
70	*					e	3.7
71					*	e	1.6
72		*				e	3.2

Table 7.10 Results from Contract Section Worth Model for Budget Scenario 2: Interstate Highway System (Continued)

Section (coded)	1982	1983	1984	1985	1986	Resurfacing Activity+	Section Length
73				*		s	1.2
74						n/s	5.5
75						a/s	4.4
76				*		c	5.2
77					*	e	1.7
78					*	c	3.3
79				*		e	1.4
80			*			e	2.5
81					*	e	1.4
82					*	e	5.4
83					*	c	3.6
84					*	c	5.1
85					*	c	3.7
86					*	c	4.1
87			*			e	4.0
88				*		e	4.4
89					*	c	3.6
90					*	a	3.7
91					*	c	4.1
92			*			e	4.0
93				*		e	3.3
94					*	e	6.6
95				*		e	5.8
96		*				a	0.7

Table 7.10 Results from Contract Section Worth Model for Budget Scenario 2: Interstate Highway System (Continued)

Section (coded)	Calendar Year 1982	1983	1984	1985	1986	Resurfacing Activity+	Section Length
97				*		e	7.3
98					*	e	3.7
99					*	c	6.6
100				*		c	4.8
101					*	a	0.7
102					*	e	7.3
103					*	c	3.7
104						n/s	6.3
105						n/s	5.3
106						n/s	6.0
107						n/s	5.8
108						n/s	5.4
109			*			c	3.5
110						n/s	7.5
111				*		c	5.8
112					*	g	2.5
113					*	e	3.2
114				*		e	1.3
115			*			e	2.9
116					*	g	2.5
117					*	e	3.4
118			*			g	1.2
Contracts	13	15	22	22	31	103	87.3
Miles	38.3	68.6	92.5	111	128.8	439.7	83.5

Note: * - indicates the year the sections would be resurfaced
+ - see Table 7.5 for resurfacing activity code
n/s - contract section not selected for resurfacing

Since the pavement section was selected for resurfacing in the third year of the analysis period, it was necessary to adjust the base year cost figures to be representative of the cost figures that can be expected in the third year. In order to accomplish this, an interest rate of six percent was assumed.

It was also assumed that after a pavement section was rehabilitated routine maintenance would be performed in subsequent years to avoid expensive rehabilitation costs in the future. For the pavement section considered above, the pavement routine maintenance cost during the third year was computed as follows:

$$RMC = \frac{\$365}{CLM} * 4.6CLM * (1.06)^3 = \$2,000$$

where:

RMC = routine maintenance cost for the entire contract section;

CLM = center-line miles of the section.

In this study it was assumed that the budget estimates of each calendar year include resurfacing cost as well as expenses for routine maintenance. As the IDOH resurfacing and routine maintenance funds are allocated separately, the budget estimates used as input to the optimization program

should either be adjusted to reflect routine maintenance costs or routine maintenance activity should be analyzed as a separate analysis. The present version of the model considers both sources of funding as a combined budget.

The corresponding results of the application of the roughness reduction optimization model under budget scenario 2 are summarized in Table 7.11. The results under other budget scenarios are included in Appendix D.

Optimal Number of Miles Resurfaced

In order to better understand the results of the optimization model, a series of graphs can be developed as discussed below. For the purpose of illustration, graphs corresponding to the contract section worth model under budget scenario 2 (see Table 7.10) are discussed here.

Figure 7.9 shows a detailed breakdown of the number of miles resurfaced by year of the analysis period using budget scenario 2. In this Figure the actual sequence in which the interstate network mileage is scheduled for resurfacing is also presented. Each bar in the Figure represents a year of the analysis period. With the exception of the base year, in every subsequent year the bars are divided into three parts. The ordinate for the lower dashed part represents the number of center-line miles scheduled for resurfacing during

Table 7.11 Results from Roughness Reduction Model for Budget Scenario 2: Interstate Highway System

Section (coded)	Calendar Year 1982	1983	1984	1985	1986	Resurfacing Activity+	Section Length
1			*			e	4.6
2				*		c	5.8
3			*			c	7.1
4	*					c	3.7
5			*			c	6.1
6				*		c	6.4
7		*				e	5.1
8			*			c	6.0
9			*			c	3.7
10			*			c	4.1
11		*				c	4.4
12				*		c	3.6
13			*			c	4.4
14		*				c	3.7
15				*		c	5.1
16			*			c	6.4
17				*		c	6.1
18		*				c	3.7
19		*				e	4.5
20	*					c	2.9
21	*					c	6.2
22			*			c	7.8
23	*					e	5.3
24			*			c	4.1

Table 7.11 Results from Roughness Reduction Model for Budget Scenario 2: Interstate Highway System (Continued)

Section (coded)	Calendar Year 1982	1983	1984	1985	1986	Resurfacing Activity+	Section Length
25					*	c	5.7
26					*	c	5.2
27						n/s	4.4
28				*		c	5.5
29				*		c	4.4
30		*				e	5.8
31	*					e	2.0
32						n/s	4.8
33				*		e	7.3
34		*				e	0.7
35					*	e	6.6
36		*				c	3.5
37					*	c	5.3
38				*		e	6.6
39	*					c	2.7
40					*	c	5.8
41	*					c	2.7
42	*					e	3.2
43			*			e	5.8
44				*		e	4.0
45				*		e	4.4
46	*					c	2.2
47			*			c	3.7
48	*					c	2.7

Table 7.11 Results from Roughness Reduction Model for Budget Scenario 2: Interstate Highway System (Continued)

Section (coded)	Calendar Year 1982	1983	1984	1985	1986	Resurfacing Activity+	Section Length
49			*			c	5.3
50			*			c	3.1
51			*			c	5.3
52				*		c	4.2
53		*				c	1.7
54	*					e	4.4
55					*	e	4.0
56				*		e	5.8
57				*		e	4.5
58		*				e	6.4
59			*			e	5.3
60			*			c	9.2
61		*				c	6.4
62		*				c	6.9
63				*		c	6.4
64	*					c	0.4
65					*	c	9.2
66		*				c	5.3
67		*				e	6.4
68		*				e	4.5
69	*					g	2.5
70					*	e	3.7
71					*	e	1.6
72				*		e	3.2

Table 7.11 Results from Roughness Reduction Model for Budget Scenario 2: Interstate Highway System (Continued)

Section (coded)	Calendar Year 1982	1983	1984	1985	1986	Resurfacing Activity+	Section Length
73					*	c	1.2
74						n/s	5.5
75					*	c	4.4
76				*		c	5.2
77					*	e	1.7
78					*	c	3.3
79				*		c	1.4
80			*			e	2.5
81					*	e	1.4
82					*	d	5.4
83				*		c	3.6
84					*	c	5.1
85					*	c	3.7
86					*	c	4.1
87					*	e	4.0
88				*		e	4.4
89					*	c	3.6
90					*	a	3.7
91					*	c	4.1
92					*	e	4.0
93						n/s	3.3
94						n/s	6.6
95					*	e	5.8
96		*				e	0.7

Table 7.11 Results from Roughness Reduction Model for Budget Scenario 2: Interstate Highway System (Continued)

Section (coded)	Calendar Year 1982	1983	1984	1985	1986	Resurfacing Activity+	Section Length
97						n/s	7.3
98					*	e	3.7
99						n/s	6.6
100					*	c	4.8
101					*	e	0.7
102						n/s	7.3
103						n/s	3.7
104						n/s	6.3
105						n/s	5.3
106						n/s	6.0
107						n/s	5.8
108					*	c	5.4
109					*	c	3.5
110						n/s	7.5
111				*		c	5.8
112					*	g	2.5
113					*	e	3.2
114				*		e	1.3
115				*		e	2.9
116				*		g	2.5
117				*		e	3.4
118				*		g	1.2
Contracts	13	16	18	26	31	104	88.1
Miles	40.9	69.7	94.5	115	126.4	446.5	84.7

Note: * - indicates the year the sections would be resurfaced
+ - see Table 7.5 for resurfacing activity code
n/s - contract section not selected for resurfacing

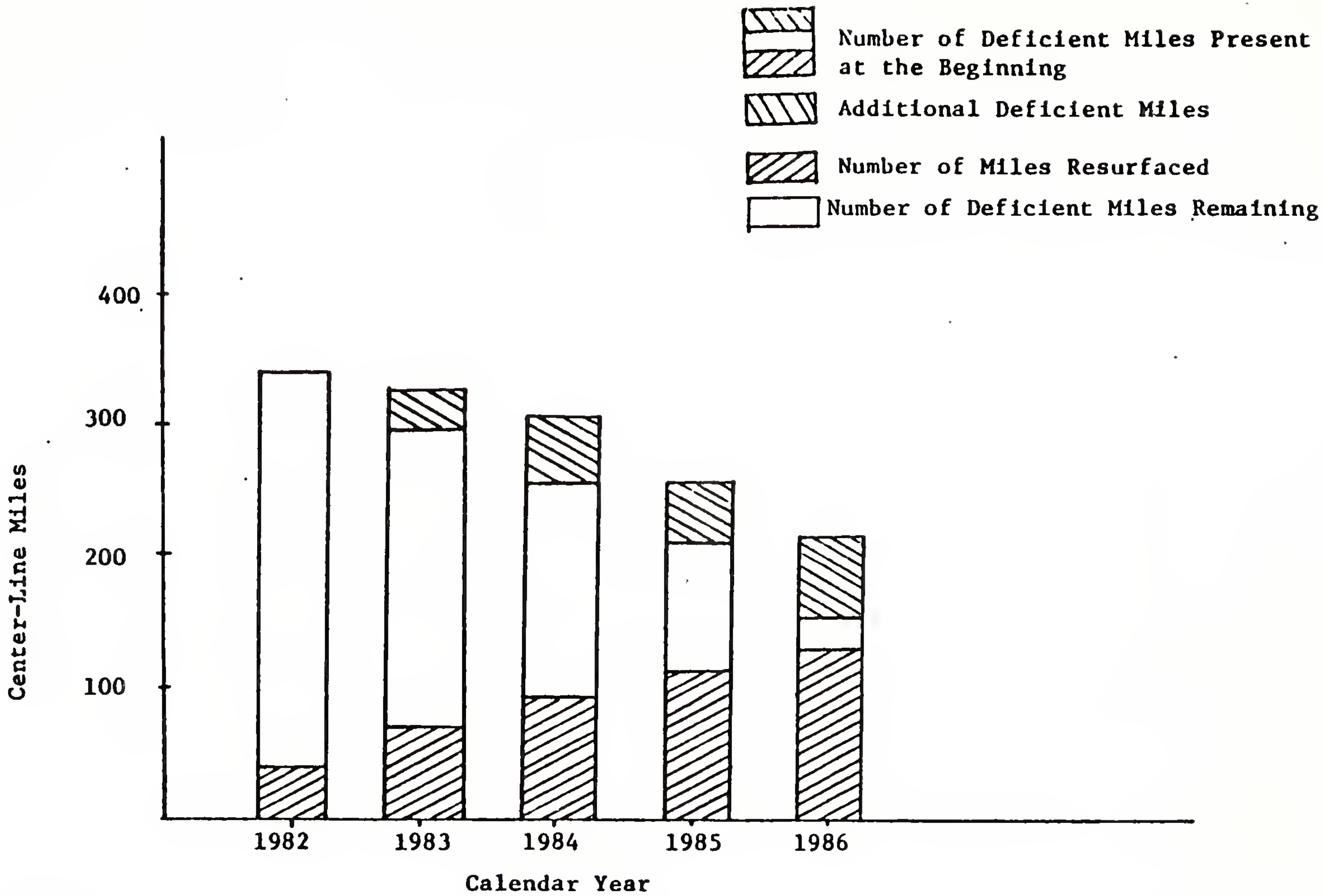


Figure 7.9 Pavement Resurfacing Mile Sequence Under Budget Scenario 2 - Contract Section Worth Model.

the calendar year in question. For example, in calendar year 2, the number of center-line miles assigned for resurfacing was 68.6 for this particular budget scenario. The ordinate for the upper dashed part corresponds to the number of center-line miles estimated to become deficient in the year in question. For calendar year 2, the number of center-line miles expected to deteriorate at a level exceeding the prescribed roughness threshold value is 26.7. The ordinate corresponding to the entire bar represents the total number of deficient center-line miles present at the start of a calendar year in question. In order to compute the number of deficient miles carried over to the next calendar year, the ordinate corresponding to the lower dashed part is subtracted from the entire ordinate. It is interesting to note that at the beginning of the analysis period about 340 center-line miles were considered deficient and at the end of the five year period only 87.2 miles (216.0 - 128.8) were considered deficient and carried over to calendar year 1987. The information of this type can also be used to monitor how many center-line miles will be optimally assigned for resurfacing in any calendar year for the budget scenario considered.

Effect of Alternate Budget Scenarios

In order to investigate the effect of different levels of budget on the effectiveness of resurfacing programs, the models were run with different budget levels given in Table 7.9. Budget Scenario 2 corresponds to the normal level of budget.

In Figure 7.10 the total optimal miles resurfaced under five alternate budget scenarios are presented for the two optimization models. Based on this Figure it can be noted that the total number of miles selected for resurfacing during the five years by the two models under a particular budget scenario is almost identical. This Figure is a good indication of the stability of the optimization models developed in this study. It can be noted that if the total budget for the five year period increases, the total optimal number of miles resurfaced also increases accordingly. The reason the number of miles are not identical is twofold. First, some pavement sections may be extremely rough and, based on roughness number alone, the roughness reduction model will most likely select these sections for resurfacing with the most expensive resurfacing strategy in order to maximize the reduction in roughness. On the other hand, for the same roughness number value, if the pavement section is relatively new and the accumulated traffic is not as high as

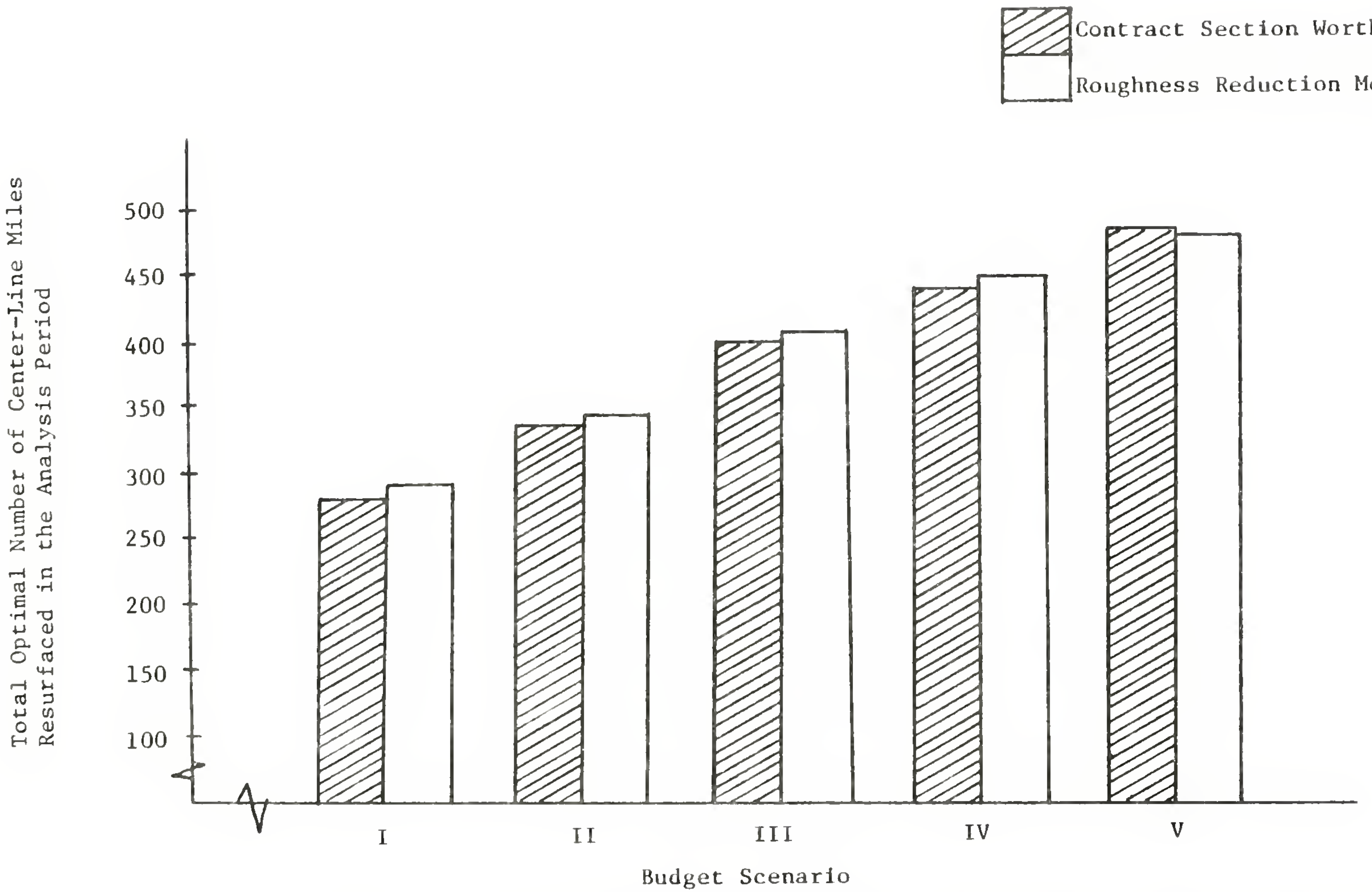


Figure 7.10 The Effect of Budget Scenario on the Number of Miles Resurfaced.

compared to the average traffic in the network and the overall pavement condition is also above average, it is unlikely that this pavement section will be scheduled for resurfacing using the contract section worth model. This is because the overall improvement that can be achieved, in terms of the CSW, is less than that for a very old pavement section with an accumulated ADT above average for that particular pavement network and with a pavement condition below average.

Figure 7.11 shows the effect of the total budget upon the optimal number of resurfacing miles and the percent of deficient mileage resurfaced during the five year analysis period using the roughness reduction model. Using the budget information furnished by IDOH, the total present worth figure of $187 millions is the approximate budget expected to be allocated to the interstate resurfacing program during the five years considered. Based on this information, Indiana can be expected to resurface about 450 center-line miles during this period of time. This would be equivalent to resurfacing about 85 percent of all the deficient center-line miles during the five year analysis period. The graph in Figure 7.11 indicates how many additional center-line miles can be resurfaced to improve optimally the overall pavement condition during the next

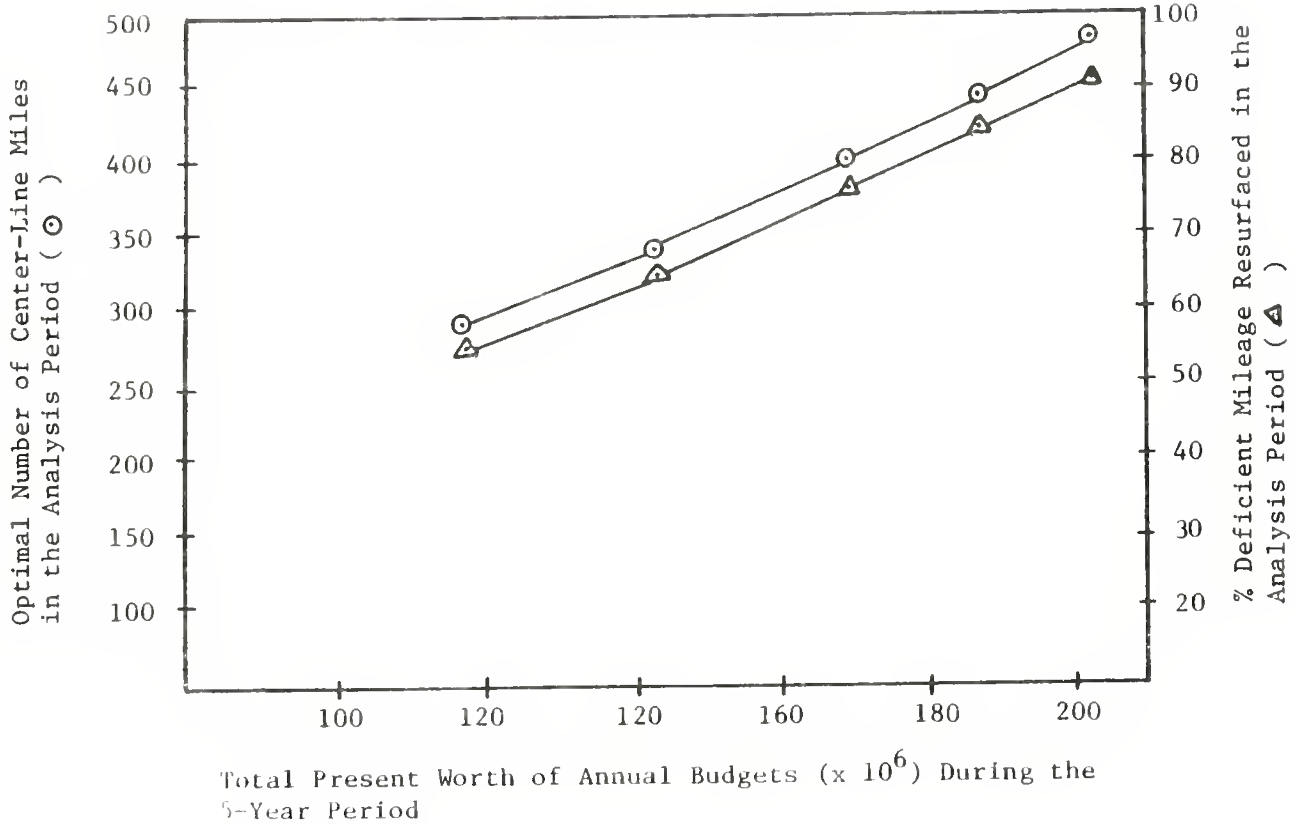


Figure 7.11 The Effect of Budget Level for Interstate Resurfacing Program Upon the Number of Miles Resurfaced - Roughness Reduction Model.

five years if the budget available for the interstate resurfacing program is increased. For example, if the budget is increased 10 percent, the corresponding present worth is about $205 millions for the five years and the number of center-line miles selected for optimal resurfacing program is about 480. This is an increase of 30 center-line miles and it represents a program that would resurface about 92 percent of the deficient mileage during the analysis period, an increase in resurfacing miles of 7 percent over the normal budget level.

The corresponding results using the contract section worth model are presented in Figure 7.12. As mentioned earlier, the aggregate results of the two optimization models are very similar in terms of the total optimal number of miles to be resurfaced. However, on a contract by contract basis, the results will obviously vary. The results on a contract by contract basis for the two optimization models are included in Appendix D.

<u>Rate of Resurfacing Per Year</u>

In order to better understand how the optimization model selects the contract sections for resurfacing under different budget scenarios, Figures 7.13 and 7.14 are presented. In Figure 7.13, the optimal number of center-line

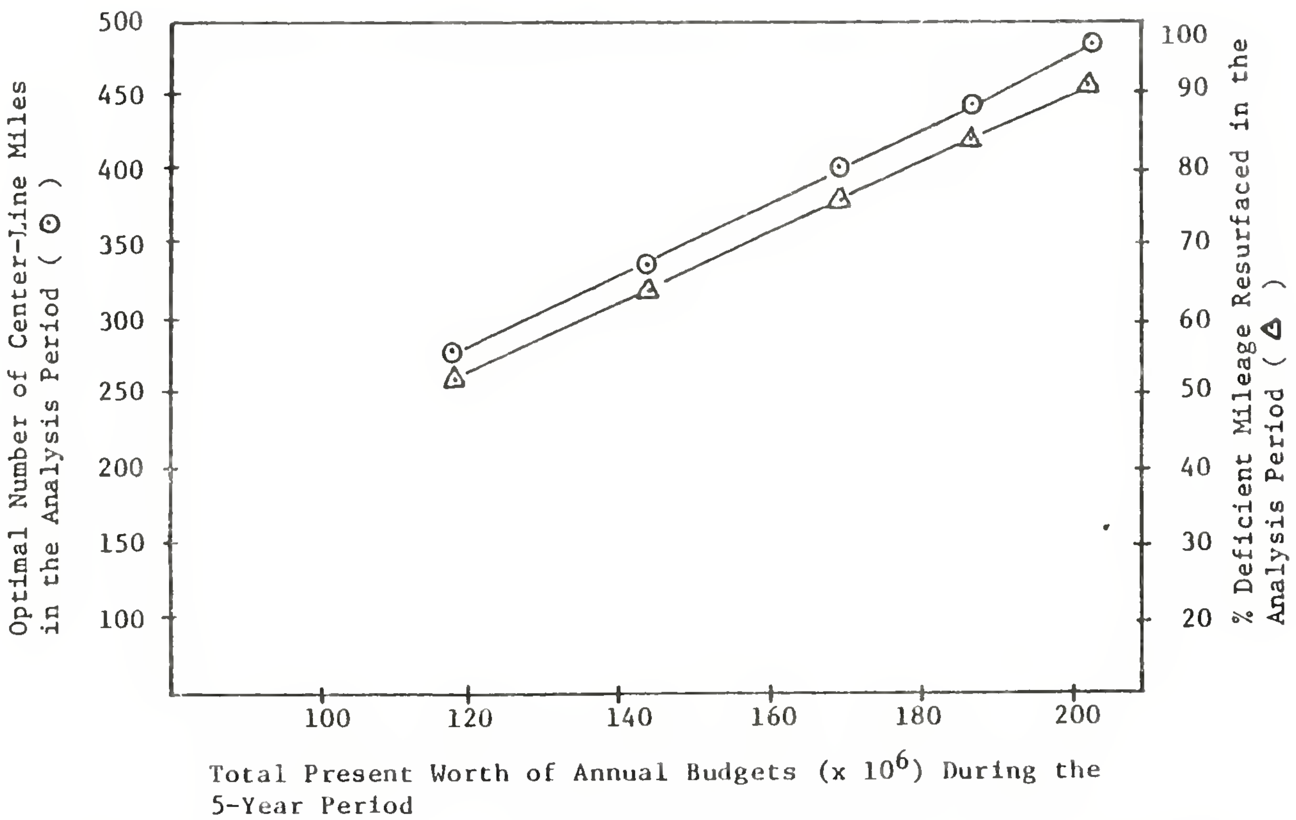


Figure 7.12 The Effect of Budget Level for Interstate Resurfacing Program Upon the Number of Miles Resurfaced - Contract Section Worth Model.

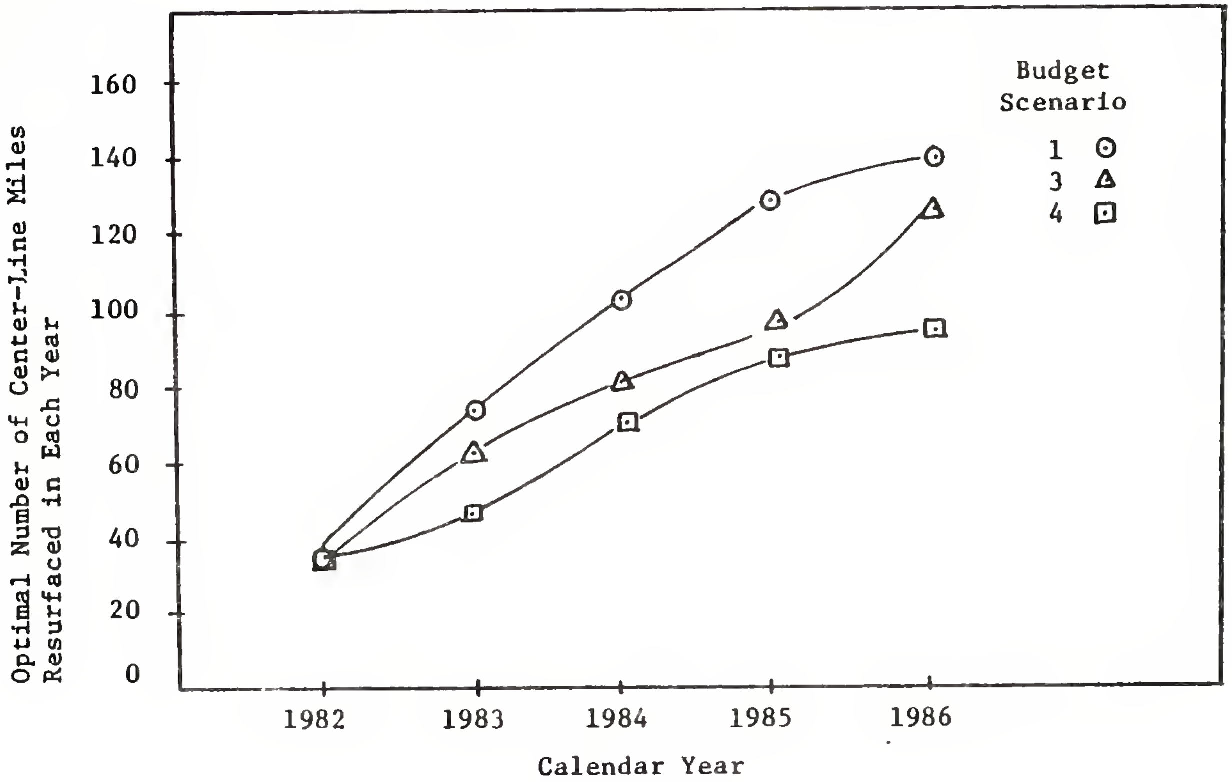


Figure 7.13 The Effect of Budget Scenarios on the Number of Miles Resurfaced - Contract Section Worth Model.

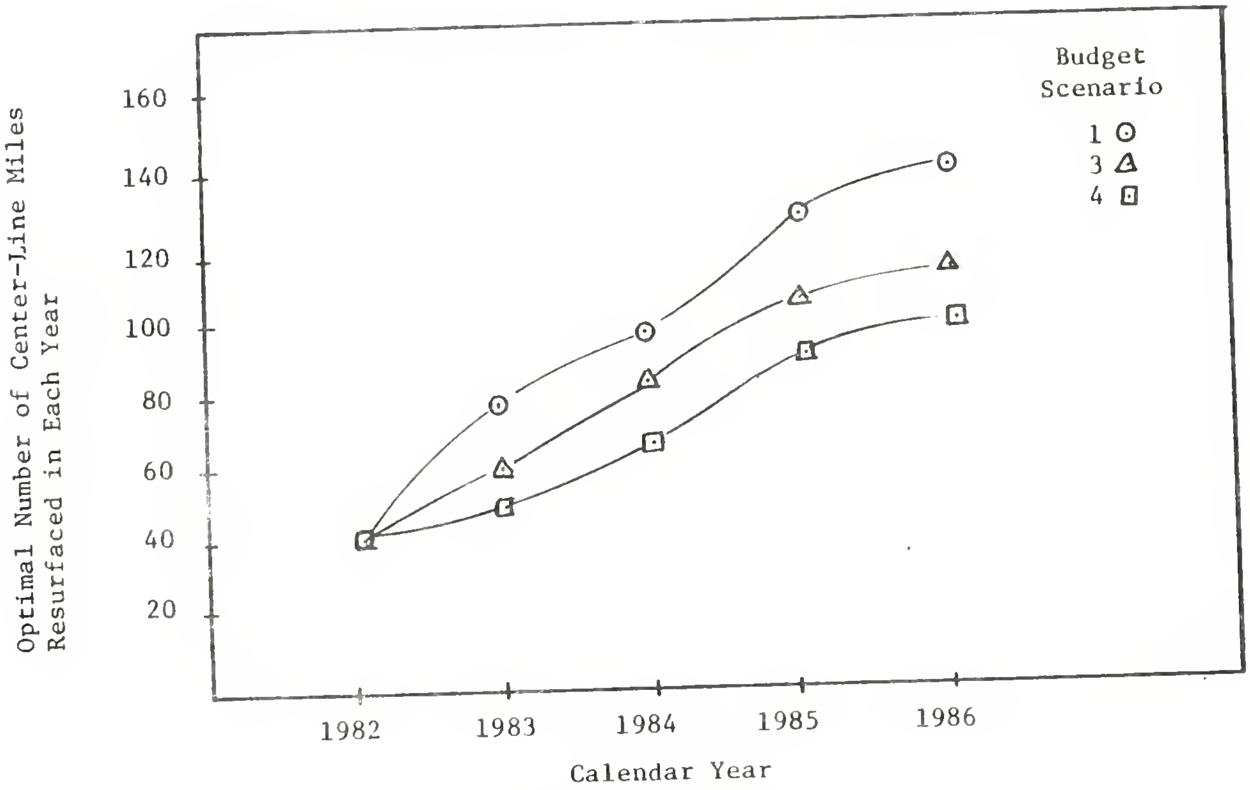


Figure 7.14 The Effect of Budget Scenarios on the Number of Miles Resurfaced - Roughness Reduction Model.

miles expected to be resurfaced each year is shown for three alternate budget scenarios using the contract section worth model. It is interesting to note how the slope of the mileage curve changes from year to year. In addition, it can be noted that the slopes for different budget scenarios are not the same. The results indicate that the optimization model selects different sets of deficient sections depending upon the budget available each year in order to maximize reduction in pavement distress. In other words, if the budget is increased to a higher level, a pavement section selected for resurfacing during a given year under the initial budget scenario may be disregarded for resurfacing during that year and carried over to the next calendar year if another pavement section is encountered that can further improve the objective function in that calendar year. For example, the results from contract section worth model can be considered under budget scenarios 1 and 4 (see Figure 7.13). During the first year the number of miles resurfaced using any of the budget scenarios is practically the same since the base year budget was the same for all scenarios. However, during the second year the number of miles resurfaced under the lower budget scenario 4 was obviously smaller as compared to budget scenario 1. The rate of increase in miles of resurfacing was much higher for budget scenario 4 than that for budget scenario 1, as indicated by

the slopes. Under budget scenario 1, the model attempted to resurface the most deteriorated sections requiring expensive resurfacing strategies in order to achieve the highest effectiveness, resulting in proportionally less resurfacing miles. However during the third year, as the worst sections already have been resurfaced, the number of resurfacing miles during this year sharply increases under budget scenario 4, as indicated by the steep slope between 1983 and 1984. However, for the high budget scenario, this problem was not encountered since there was enough budget to resurface the worst alternatives as well as a few other defective sections.

Optimality of the Solution

It is important to mention that the solution achieved by this procedure is not entirely integer optimal. However, the solution is very close to the optimal linear programming solution. Previous research studies conducted by Industrial Business Machines (IBM) in the application of integer programming codes, in particular those which are based on the branch and bound technique as used in this research project, have shown that only minimal improvements are achieved after the problem has attained at least 97 percent of the optimal LP solution. Beyond this level, the amount of computer time required to obtain an increase in optimality by even a small amount is disproportionately high [85].

In Table 7.12 the results obtained from the budget sensitivity analysis performed on the two optimization models is summarized. It can be noted that in only one of ten budget scenarios analyzed the first feasible integer solution was less than 97 percent of the optimal LP solution. This corresponded to budget scenario 5, contract section worth model, and it was 94.5 percent of the optimum LP solution. The fact that 90 percent of the times the first integer solution obtained was within 3 percent of the optimum LP solution is a good indication of the robustness of the formulation developed in this study.

Table 7.13 shows the zero-one integer solution for the roughness reduction model under budget scenario 2. The % LP optimum shown in this Table was also plotted against the number of iterations required to achieve this value. This graph is shown in Figure 7.15. In this particular scenario, the execution of the optimization program was stopped after 23701 iterations when the fifth feasible integer solution was obtained. It can be noted in Figure 7.15 that the increase in optimality achieved since the first feasible IP solution is minimal as compared to the number of interations (pivots) required to increase the solution from 99.21 percent to 99.36 percent.

Table 7.12 LP and IP Solutions Obtained from Budget Sensitivity Analysis for (a) Contract Section Worth Model

Present Worth ($ millions)	Budget Scenario	Contract Section Worth Model Characteristics					
		LP ($\times 10^{11}$)	Iteration	IP ($\times 10^{11}$)	Iteration	Branch	%Opt.
203.78	1	18.69	2616	18.45	8688	48	98.7
186.71	2	18.22	3111	17.92	25839	85	98.3
169.94	3	17.68	3284	17.23	8920	49	97.4
144.08	4	16.78	3911	16.28	8251	34	97.0
118.44	5	15.72	3559	14.86	9876	63	94.5

Table 7.12 LP and IP Solutions Obtained from Budget Sensitivity Analysis for (b) Roughness Reduction Model (Continued)

Present Worth ($ millions)	Budget Scenario	Roughness Reduction Model Characteristics					
		LP ($x\ 10^5$)	Iteration	IP ($x\ 10^5$)	Iteration	Branch	%Opt.
203.78	1	15.80	2497	15.44	6642	32	97.8
186.71	2	15.40	2678	15.30	23701	63	99.4
169.94	3	14.96	2998	14.75	4169	23	98.6
144.08	4	14.23	2681	13.95	5925	50	98.1
118.44	5	13.37	3372	13.21	8283	24	98.8

Table 7.13 Results of Zero-One Integer Solution for Roughness Reduction Model Under Budget Scenario 2

IP Solution	Branch	Pivot	% LP opt.*
1527797.75	26	4430	99.21
1528457.25	40	11216	99.26
1528550.75	46	14757	99.26
1529431.38	57	18590	99.32
1530011.25	63	23701	99.36

LP opt. = 1539876.75

*% LP opt. = $\left[\frac{\text{IP Solution}}{\text{LP Solution}}\right] \times 100$

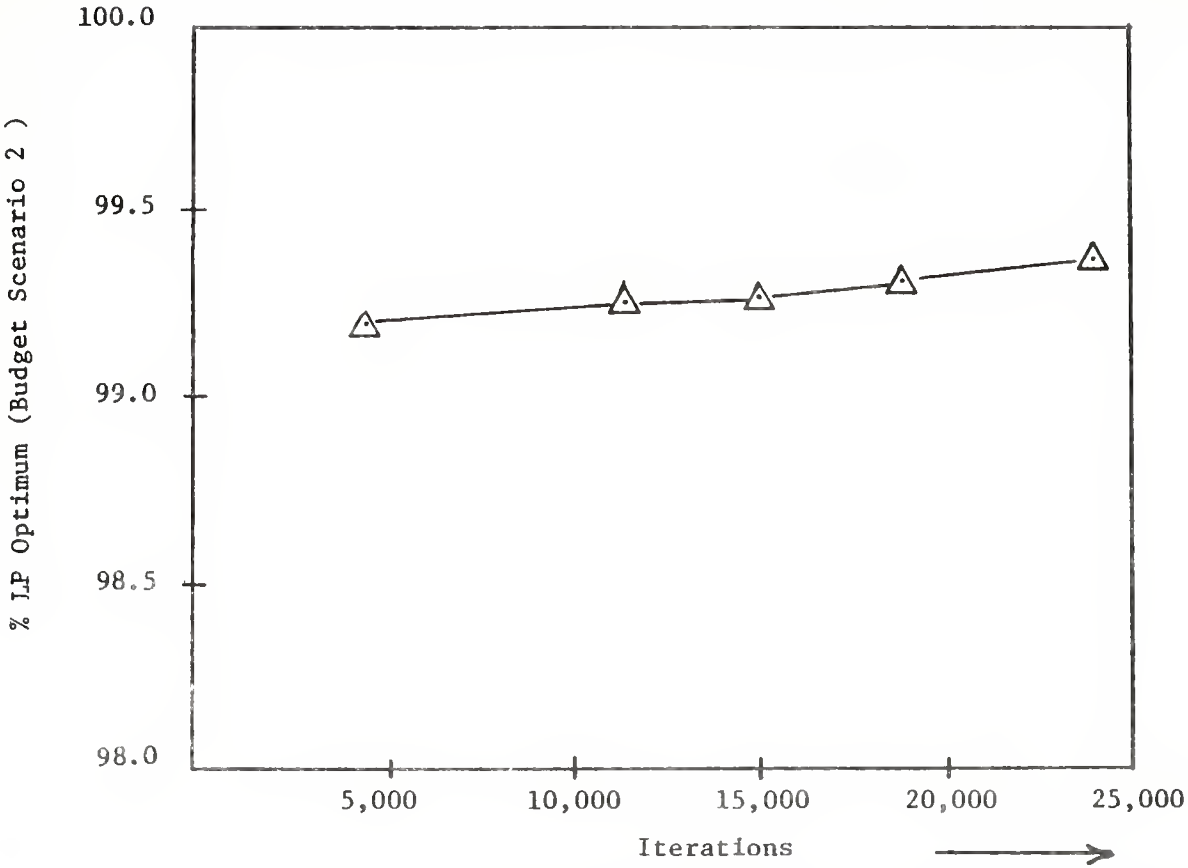


Figure 7.15 Relationship Between Number of Iterations and % LP Optimum for Roughness Reduction Model Under Budget Scenario 2.

In summary, it is recommended that if the IP solution achieved using the proposed procedure is within 3 percent of the optimal LP solution, the execution of the program should be terminated.

Detailed Summary of Results - Contract Section Worth Model

Tables 7.14 (a) through 7.14 (c) show a detailed summary of the results obtained using the contract section worth model under budget scenario 2. Table 7.14 (a) shows the sequence in which the pavement sections are entered into the analysis as well as the rate in which the optimization model selects them for resurfacing during the 5- year analysis period. The total number of deficient miles present at the beginning of each year is also included and updated each calendar year. The expected budget for each calendar year as well as the percent of budget allocated by the optimization routine is also included in this Table.

Table 7.14 (b) shows the number of contract sections and the corresponding number of center-line miles selected for resurfacing during each calendar year according to resurfacing activity. The total number of miles resurfaced during the 5-year period according to resurfacing activity used are also included in this Table. Pavement resurfacing costs and routine maintenance costs associated with each

Table 7.14(a) Detailed Summary Under Budget Scenario 2 Using Contract Section Worth Model.

Parameter Description	Year in the Analysis Period 1982	1983	1984	1985	1986	Total 5-yr.
New Sections Entered In	70	6	12	13	17	118
Total No. of Sections Present	70	63	60	51	46	---
No. Sections Selected by Model	13	15	22	22	31	103
Number of New Miles Entered In	336.7	26.7	48.4	50.2	64.9	526.9
Total Number of Miles Present	336.7	324.6	304.4	262.1	216.0	---
No. of Miles for Resurfacing	38.8	68.6	92.5	111.0	128.8	439.7
Pct. of Miles for Resurfacing	11.5	21.1	30.4	42.4	59.6	83.5
Available Budget ($ Millions)	17.0	32.0	46.0	60.0	75.0	230.0
Budget Spent ($ Millions)	16.67	29.0	43.0	53.95	66.22	208.8
Percent of Budget Spent	98.04	90.66	93.61	90.11	88.29	90.8
No. of Miles Carried Over	297.9	256.0	211.9	151.1	87.2	---
No. of Sections Carried Over	57	48	38	29	15	---

Table 7.14(b) Detailed Summary Under Budget Scenario 2 Using Contract Section Worth Model (Continued)

Resurf. Strategy (coded)*	Resurf. Cost ($/clm)	Routine Maint. ($/clm) +++	Contr. Freq. 1982	Resurf. Miles 1982	Contr. Freq. 1983	Resurf. Miles 1983	Contr. Freq. 1984	Resurf. Miles 1984	Contr. Freq. 1985	Resurf. Miles 1985	Contr. Freq. 1986	Resurf. Miles 1986	Contr. Freq (5-yr.Total)	Resurf. Miles (5-yr.Total)
a b	310,000 345,000	900 765									3	13.6	3	13.6
c d	371,000 393,000	635 500	4	8.8	7	30.4	12	51.0	13	74.7	14	64.6	50	229.5
e f	412,000 429,000	365 235	8	27.5	8	38.2	9	40.3	9	36.3	12	45.6	46	187.9
g	445,000	105	1	2.5			1	1.2			2	5.0	4	8.7
		Total	13	38.8	15	68.6	22	92.5	22	111.0	31	128.8	103	439.7

Note: * Refer to Table 7.5 for resurfacing activity code
+++ clm meane center-line miles

Table 7.14(c) Detailed Summary Under Budget Scenario 2 Using Contract Section Worth Model (Continued)

Resurf. Strategy (coded)*	Resurf. Cost ($/clm)	Routine Maint. ($/clm)+++	TPRC+ (x 10^6) 1982	TRMC++ (x 10^3) 1982	TPRC (x 10^6) 1983	TRMC (x 10^3) 1983	TPRC (x 10^6) 1984	TRMC (x 10^3) 1984	TPRC (x 10^6) 1985	TRMC (x 10^3) 1985	TPRC (x 10^6) 1986	TRMC (x 10^3) 1986	TPRC (x 10^6) (5-yr. Total)	TRMC (x 10^3) (5-yr. Total)
a	310,000	900									5.64	16.38	5.64	16.38
b	345,000	765												
c	371,000	635	3.46	5.92	11.28	21.69	22.53	38.57	34.99	59.89	32.07	54.89	104.33	180.96
d	393,000	500												
e	412,000	365	12.01	10.64	17.68	15.67	19.77	17.52	18.88	16.73	25.14	22.27	93.48	82.83
f	429,000	235												
g	445,000	105	1.18	.28			.64	.15			2.98	.70	4.8	1.13
Total			16.65	16.84	28.96	37.36	42.94	56.24	53.87	76.61	65.83	94.24	208.25	281.13
% Budget Spent (without TRMC)			97.94		90.5		93.36		89.78		87.78		90.5	
% Budget Spent (including TRMC)				98.04**		90.66**		93.61**		90.11**		88.29**		90.67

Note:

\+ TPRC means total pavement resurfacing cost
++ TRMC means total routine maintenance cost
+++ clm means center-line miles
* refer to Table 7.5 for resurfacing activity code
** includes accumulated routine maintenance costs attributed to pavement sections resurfaced on previous years

resurfacing activity are also listed in this Table.

Table 7.14 (c) shows the total pavement resurfacing and routine maintenance costs by calendar year and type of resurfacing activity used. The % of available budget spent, with and without pavement routine maintenance costs, are also shown in this Table for each calendar year. Total pavement expenditures for the five year analysis are also summarized according to resurfacing activity applied.

Based on these Tables, the following remarks can be made:

1. A total of 103 out of 118 contract sections were selected for resurfacing during the 5-year period. This corresponded to about 440 center-line miles out of the 527 miles identified in this study as deficient pavement sections. This means that 83.5 percent of the sections identified as deficient were selected for resurfacing during the 5-year period by the optimization routine.

2. Over 90 percent of the available budget was assigned in an optimal manner during the entire 5-year period.

3. Resurfacing activities 'c' and 'e' were the most frequently selected by the optimization routine since 96

out of the 103 contract sections selected for resurfacing were assigned either one of these two activities. This corresponded to 417.4 miles or approximately 94 percent of the deficient miles considered in this study. In most cases, the resurfacing strategy selected by the optimization model was the most expensive of the three feasible rehabilitation strategies pertaining to the pavement section in question. Likewise, it was the resurfacing alternative that contribute most to the objective function value of the contract section worth model.

4. The remaining 10% of the budget over the five year analysis period was never assigned. It can be recalled that the smallest unit for resurfacing established for this study was the pavement contract section. Therefore, in some cases, during a given calendar year, there may be money left sufficient to resurface only a fraction of a set of contract sections. However, this was not done by the optimization routine since it was not feasible to resurface only a part of the contract section.

In summary, the results presented in Tables 7.10 through 7.14 and in Figures 7.9 through 7.14 can be used by highway administrators and decision-makers as a guide in the process of making budget requests and establishing resurfacing priorities for pavement networks during a given five-year horizon.

Verification of Results - Graphic Interactive Technique

The graphic interactive approach, described in Chapter 3, was used to verify part of the results obtained by the optimization routine. It should be noted that the graphical method can only be used to verify the results on a yearly basis and for one route and one traffic direction at a time. In order to show the application of the graphical technique, the data for Interstate 65 North for 1982 calendar year were selected.

The first step was to plot the performance factors associated with each pavement contract section located in a particular route in a particular year against a common reference point. The milepost number was used as the common reference point for all plots.

The graphs corresponding to four of the performance factors considered in this study namely, roughness number, increase in roughness, pavement age, and pavement condition index, for Interstate 65 North and 1982 calendar year are shown in Figures 7.16 (a) through 7.16 (d).

Based on Figure 7.16 the following remarks can be made:

1. First, the results shown in Figure 7.16 by itself might be misleading. The main reason is the fact that identical roughness number readings for asphalt and concrete pavement surfaces actually are interpreted differently at the time of using this number for establishing resurfacing priorities. For example, if an asphalt pavement section showed a roughness reading of 1400 counts per mile it is actually considered a deficient pavement section whereas a concrete pavement section that has exactly the same roughness number value is considered to be in satisfactory condition.

2. A concrete pavement section that has been in service for 12 years may be considered relatively a new pavement whereas an asphalt pavement of the same age under similar traffic and climatic conditions may be considered an old pavement.

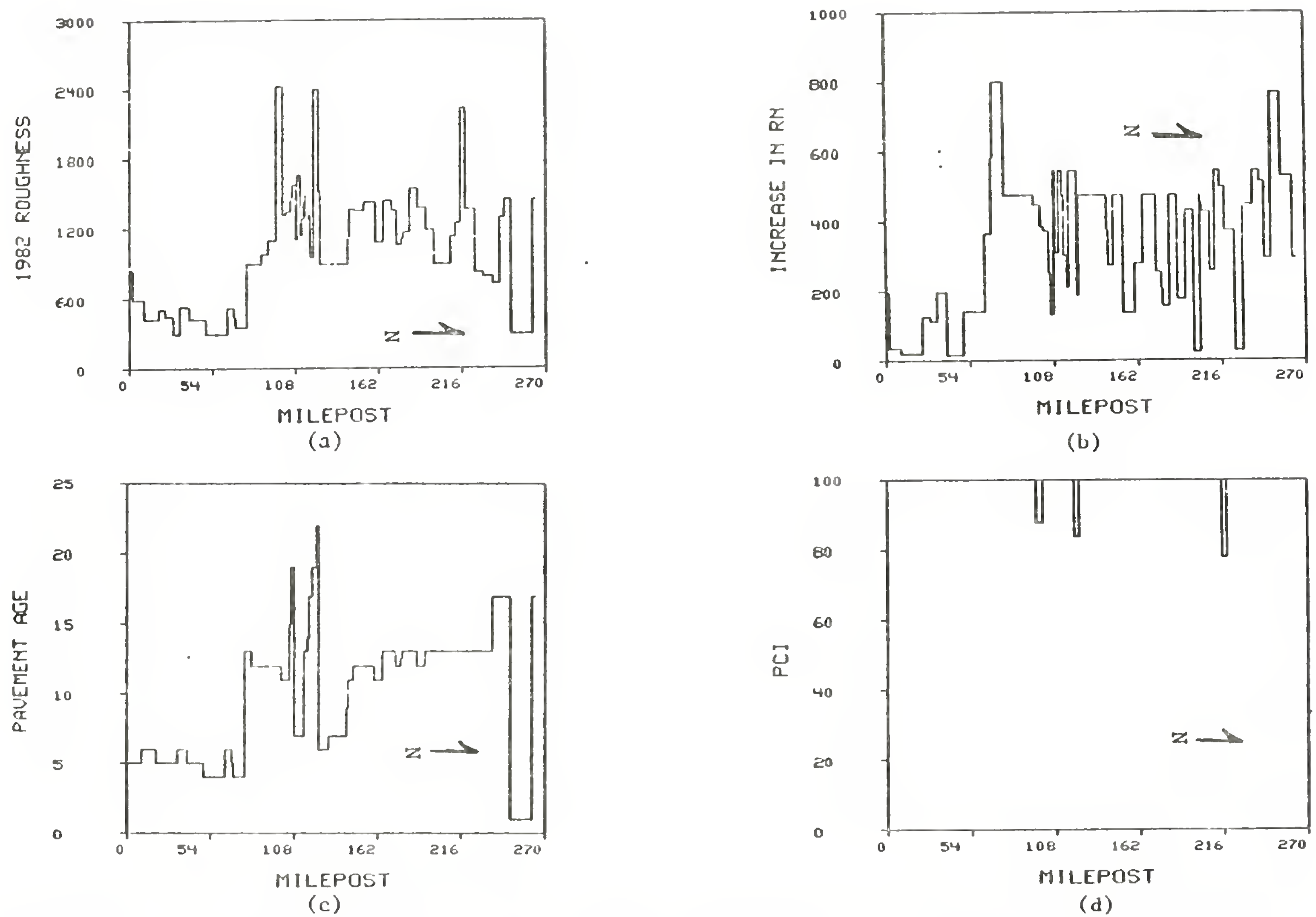


Figure 7.16 Analysis of Performance Factors Using the Graphic Interactive Technique - Interstate 65 North

3. It is not possible to assess the roughness level of pavement sections from roughness number measurements taken in one interstate route without comparing these measurements with those from the entire network. For example, the range in roughness number for one interstate route can be between 300 and 1200 counts per mile whereas in another interstate route the range in roughness number values can be between 900 and 3000 counts per mile. Therefore, the resurfacing decision can not be made on a route basis because the pavement sections located in the latter route are in more needs of major rehabilitation as compared to the first route. It might be even possible that within a given route all pavement sections are in satisfactory condition as compared to the entire pavement network.

In summary, an attempt to use the results shown in Figure 7.16 without prior knowledge of other pavement characteristics can lead to a poor engineering judgment in selecting candidate projects for resurfacing.

In order to be able to use these data, the equivalent performance index (EPI) curves developed in this study for each performance factor, pavement type, and highway class were used to transform each of the performance factors into a standard scale of 0 to 100. The value of 0 represents a very poor performance for the factor in question, while 100

represents an excellent performance. The new set of graphs generated using this graphical procedure for Interstate 65 North and for the same performance factors are shown in Figures 7.17 (a) through 7.17 (d).

The pavement condition index (PCI) graph (see Figure 7.17(d)) shows the three pavement sections that exceeded the roughness number threshold value for concrete pavements of 2000 counts per mile during 1982. Since pavement condition information was not available for the remaining pavement sections within this route, a PCI of 100 was assumed. This value was assumed to check if other pavement sections located on Interstate 65 North are in worst overall condition as compared to these three sections even though the highest possible PCI was assigned to them.

At this stage, if no other performance factors are considered, a pre-established cut-off value can then be plotted on these graphs and by inspection the pavement sections which fall below the cut-off value on each graph can be selected for follow-up investigation. These pavement sections would represent the deficient pavement sections for that particular interstate route. For this particular case, if the cut-off value is set to 20, only three pavement sections should be followed for investigation on the basis of roughness as the performance factor. If increase in

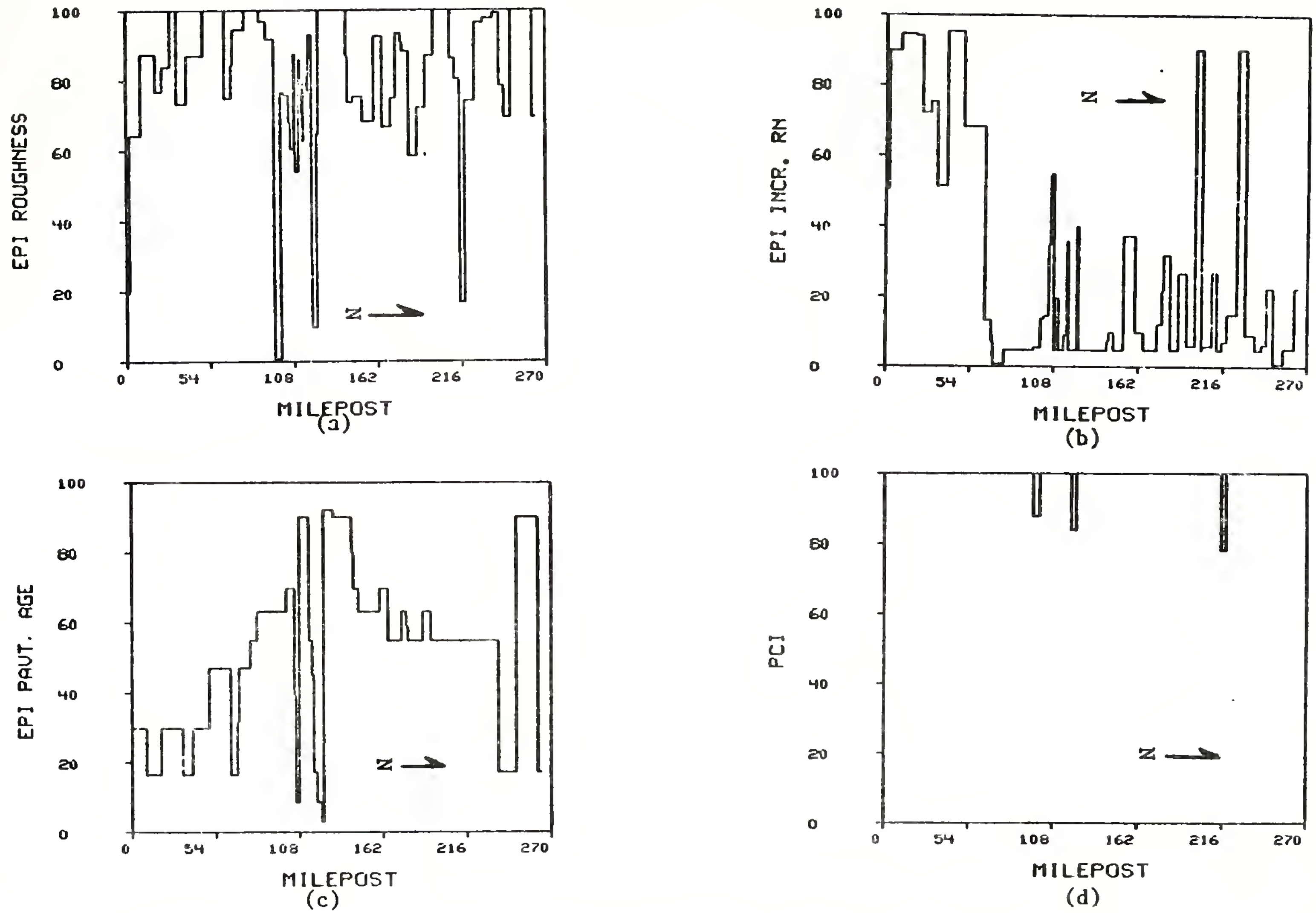


Figure 7.17 Graphical Analysis of Equivalence Performance Indices - Interstate 65 North

RN is considered as the performance factor, 27 pavement contract sections can be considered deficient. On the other hand, if pavement age is considered, 9 pavement contract sections can be identified as deficient. At this stage, one question which might arise is what performance factor should be considered as the primary controlling factor. Another question may involve the weighing of these factors.

In order to be able to answer these questions, the overall aggregated weight (OAW) was developed. The overall aggregated weight for each pavement contract section within a given route is computed by multiplying the equivalent performance index complement (CEPI) of each performance factor by its corresponding weight (see Table 7.8). The general equation used is of the following form:

$$OAW = CEPI_a * W_a + CEPI_b * W_b + CEPI_c * W_c + CEPI_d * W_d \tag{7.1}$$

where:

OAW = overall aggregated weight, $0 < OAW < 100$;

CEPI = equivalent performance index complement for factor

in question, 'a' through 'd', CEPI = 100 - EPI;

W = relative weight assigned to each performance factor

The complement EPI was used in the computation of the overall aggregated weight instead of the EPI in order to conform to the requirements of the objective function. The objective function was formulated as a maximization of the overall weighed reduction in pavement distress. For this reason, the complement of the EPI appears to be the most appropriate factor for such formulation. Using this graphical procedure, the pavement contract sections that have a high OAW are considered deficient. The relative weights used to compute the OAW are shown in Table 7.8 presented earlier in this chapter. The overall aggregated weights for pavement contract sections located along Interstate 65 North during 1982 are plotted in Figure 7.18. Based on Figure 7.18, and setting the OAW cut-off value to 60, only three of the pavement contract sections located along Interstate 65 North are considered deficient. This corresponded to 11.2 center-line miles out of the 265 center-line miles located along Interstate 65 North. That is, approximately 4.3% of the pavement mileage within this route.

The overall aggregated weight, as defined herein, does not take into account the effect of traffic. The effect of traffic is considered to be as important as the overall

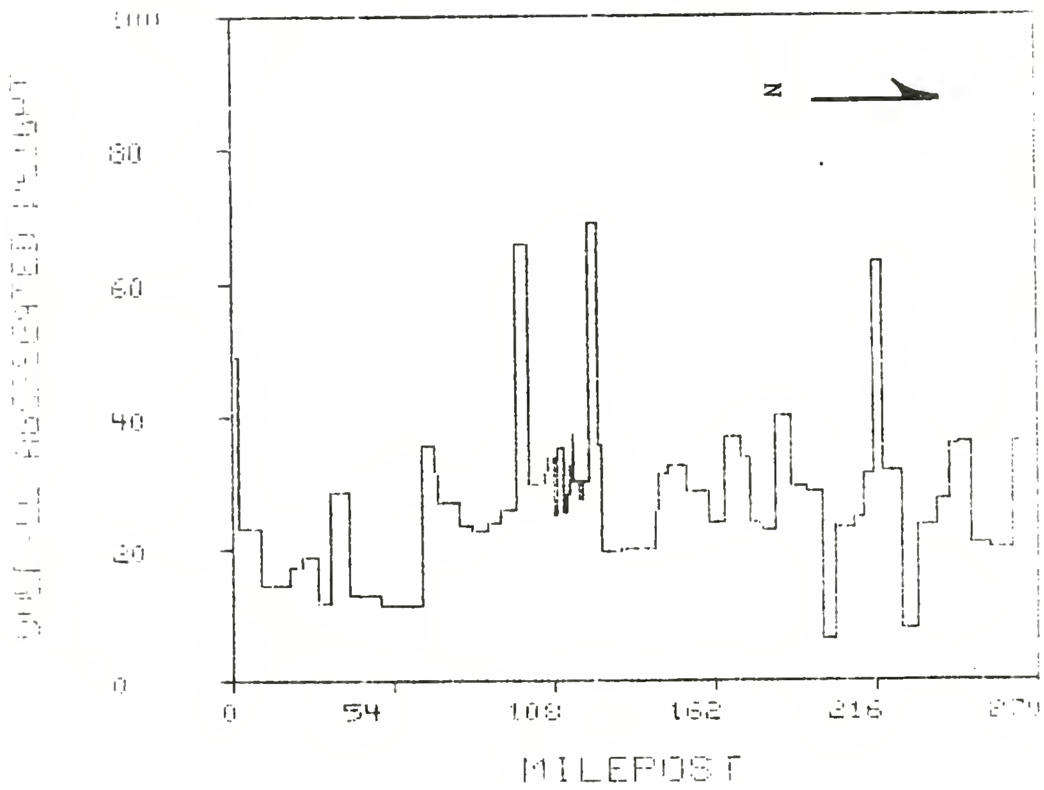


Figure 7.18 Graphical Analysis of Overall Aggregated Weight (OAW) for Interstate 65 North.

contribution of the other four performance factors combined. In order to incorporate the effect of traffic into the graphical analysis, the contract section worth (CSW) was developed. The CSW value is a quantitative measure of the overall worth of each pavement contract section. The CSW is computed by multiplying the overall aggregated weight (OAW) of each pavement section by its accumulated traffic (TADT) during its service life. The equation used is shown below:

$$CSW_i = TADT_i * OAW_i \qquad (7.2)$$

where:

CSW_i = contract section worth associated with pavement contract section i;

$TADT_i$ = accumulated directional ADT for section i computed using equation 3.1;

OAW_i = overall aggregated weight for section i computed using equation 7.1.

The contract section worth values for pavement sections located along Interstate 65 North during 1982 are plotted in Figure 7.19. The range in contract section worth values for pavement sections located on Interstate 65 North is between 20,000 and 450,000. It should be pointed out that the cut-off value for the contract section is different as compared to the OAW cut-off value. This is because the accumulated

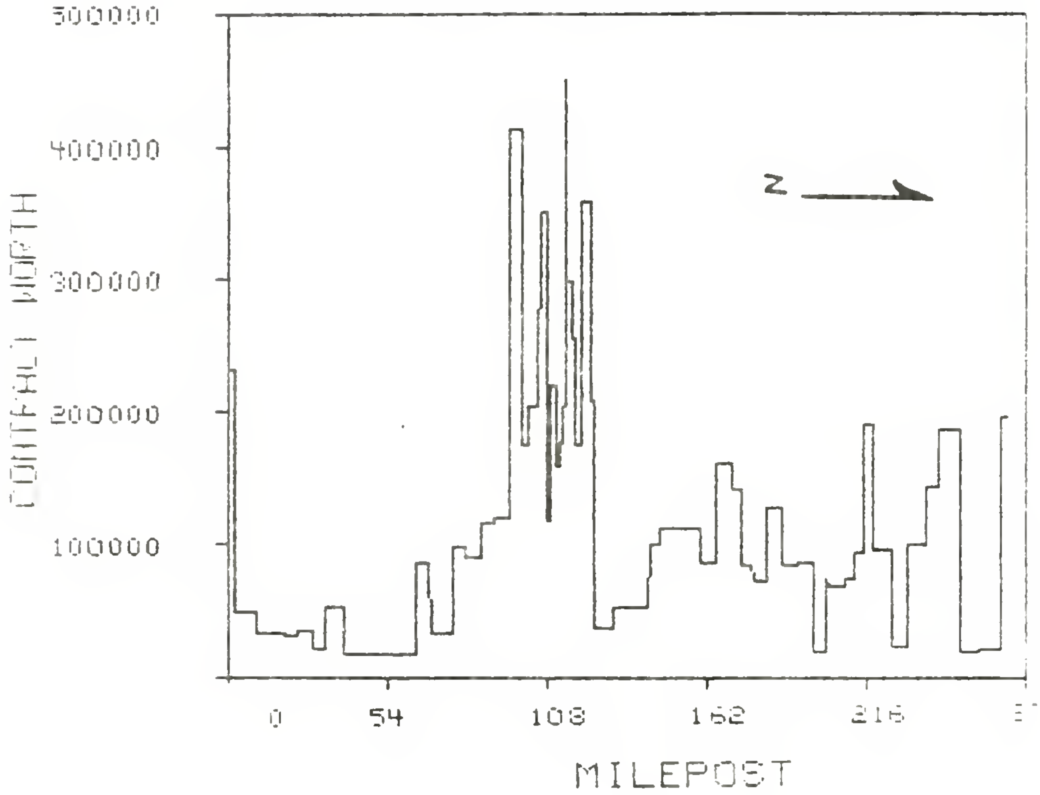


Figure 7.19 Graphical Analysis for Contract Section Worth - Interstate 65 North

traffic was multiplied directly to the OAW instead of transforming it to a common scale as it was done with the other performance factors considered.

For a cut-off value of 400,000, two pavement sections were identified as deficient, based on the contract section worth definition. These are located approximately 93.5 miles and 114 miles north from Kentucky-Indiana State Line. By visual inspection, the pavement sections are approximately 4.5 and 1.2 miles long, respectively. It should be mentioned that the first pavement section was one of the three concrete pavement sections that had a roughness number greater than 2000 counts per mile and also one where pavement condition was measured. The other two sections were not even close to the deficient pavement sections obtained by the graphical procedure. Recall that in order to compute the CSW for the remaining pavement sections, the pavement condition rating was assumed to be 100. In other words, even though a PCI of 100 was assumed for all the remaining pavement sections, still some of these sections showed a greater need of rehabilitation, based on the CSW definition, as compared to those that had a PCI less than 100 and a roughness number greater than 2000 counts per mile. These results show the importance of incorporating all the performance factors which are most likely to predict pavement

deterioration into the optimization model.

Finally, it should be noted that traffic by itself is not a good parameter to base resurfacing decisions, since a pavement section may have either a very high accumulated traffic or a very high current ADT and still may have low roughness number and other associated performance factors (see Figure 7.20(a) and Figure 7.20(b)).

The graphical procedure described in the previous paragraphs was applied only during the first year of the analysis period and for only one interstate route namely, Interstate 65, and for one traffic direction, northbound lane. In order to use this procedure for years two through five, it is necessary to use the predicted roughness numbers as well as the predicted values for other parameters such as the increase in roughness between the two contiguous years, accumulated traffic, and so on for different routes and traffic directions as well.

In summary, it can be stated that the combination of a graphical approach with an optimization technique is a very powerful tool which can be incorporated as a part of the IDOH pavement management system.

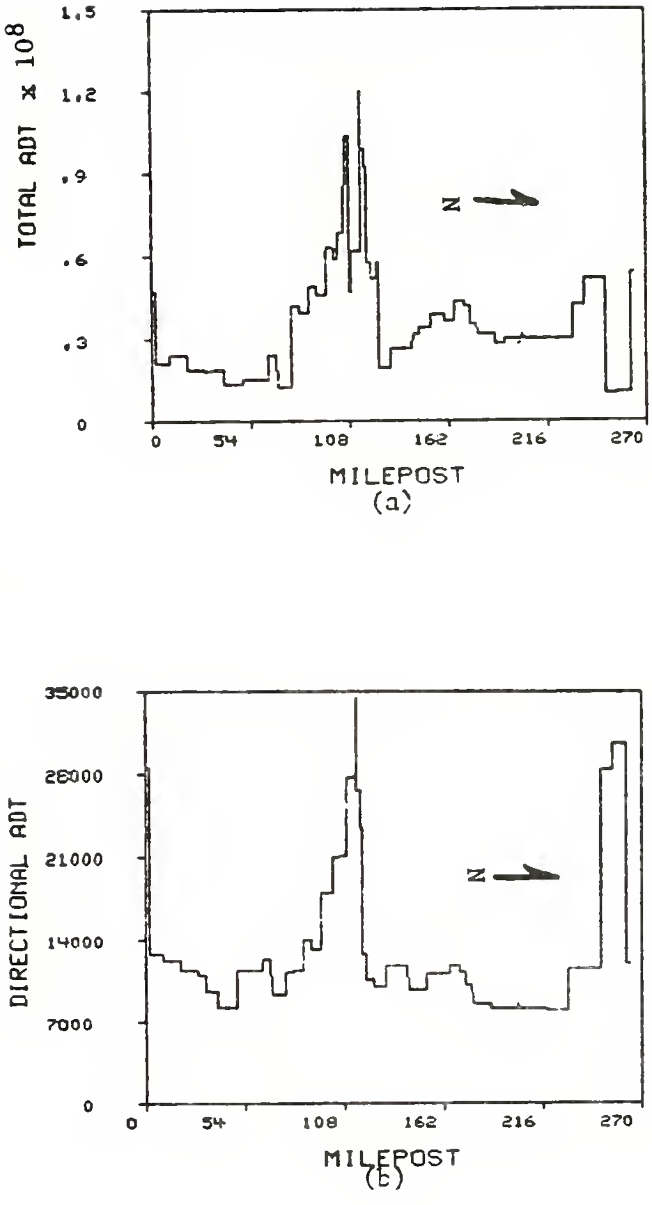


Figure 7.20 Graphical Analysis for
(a) Total ADT and (b) Current ADT
for Interstate 65 North

CHAPTER 8

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

This research was aimed at the development of a procedure including an optimization routine that can be used by the Indiana Department of Highways in establishing resurfacing priorities under limited financial resources. The procedure was primarily developed to answer questions such as:

1. What existing pavement contract sections are in need of repair during the base fiscal year?

2. What resurfacing strategy should be adopted for those contract sections already selected in order to use the available budget in the most cost- effective manner?

3. How many additional contract sections can be resurfaced if the budget is increased by a specified amount?

4. How many miles will these additional contract sections represent?

The importance of using the pavement contract section as the decision variable was recognized at the initial stages of the project. Furthermore, there was a need to establish a systematic way to analyze pavement performance

data that the State has collected effectively on a continuing basis but not analyzed so far.

The data analysis procedure developed in this study identifies contract sections that are in need of rehabilitation. The optimization model then assigns the appropriate resurfacing strategy for rehabilitation of these sections in an optimal manner. The model takes into account future routine maintenance costs once the contract section is chosen for rehabilitation. In its present format, the optimization model is formulated to address a five-year rehabilitation program. However, a short term planning horizon can be incorporated with relatively minor changes.

Limitations of the Optimization Models

The optimization model developed in this study has several limitations which should be considered if it is to be used as a part of Indiana's pavement management program. These limitations are described briefly in the following paragraphs.

A rigorous solution of the integer programming formulation of the problem consumes a great amount of computer time. This difficulty can be overcome if a near optimal solution that is within three percent of the optimal linear programming solution can be used as the final output. It

should be pointed out that the execution of the optimization model with the LINDO computer program has produced, in most cases, an integer solution that has met this criterion in one iteration. Therefore, great savings in computer time can be made if this criterion is accepted as a standard.

The criterion used in this study to select a resurfacing strategy was based primarily on the current ADT of the pavement section in question. The typical resurfacing strategies used by IDOH were divided into three categories depending upon the ADT of the pavement sections considered. This procedure relies on the fact that in the design of pavement structures traffic plays the most important role.

Since the critical issue is to rehabilitate the maximum number of pavement sections with the limited budget available for the analysis period in question, the proposed procedure assigns the resurfacing strategies in such a way that the pavement can withstand the traffic repetitions at least for the analysis period.

It is important to keep in mind that every resurfacing strategy assigned to each pavement section is adequate for at least the analysis period in question. However, a section resurfaced during a given 5-year period may need further major rehabilitation in the next analysis period if

the resurfacing strategy selected in the initial analysis period is the least effective of the feasible strategies.

It is desirable to include an overlay design algorithm as a part of the pavement management system envisioned for the state highway network in Indiana rather than adopting only typical rehabilitation strategies practiced.

For the purpose of incorporating overlay design in the decision process, it is necessary to consider an appropriate design method such as the AASHTO Design Method, The Asphalt Institute, Corps of Engineers, and so on. A subroutine can then be written to generate information on overlay as one of the strategies that can be included as input to the optimization program. Although this task was not in the scope of the present study, it is felt that an overlay design algorithm is, in fact, a critical part of any pavement management program.

The pavement routine maintenance costs included in the optimization model are estimates from another research project currently being conducted at Purdue [94]. It should be realized that these cost figures are estimates of a sample of pavement sections throughout the State and, therefore, should be treated as such.

The performance curves developed in this research project for pavement roughness, pavement age, and change in roughness for various types of pavements, were generated using performance data from only one year, 1981. In future, these curves might need further refinement to be applicable to the current condition of the pavement network at the beginning of an analysis period in question.

It should be pointed out that the purpose for developing the performance curves and the equivalent performance index concept was to consider all performance factors included in the study on a commensurable scalar basis that can be easily interpreted by the decision-makers.

In so far as the weights used to represent the importance of each performance factor considered in this study, it should be noted that these are subjective in nature, selected after interviewing the members of Indiana's Pavement Management Task Force. In future years these performance weights should be carefully evaluated and adjusted.

The linear regression equations, developed for each pavement type and interstate route combination, for predicting roughness numbers for years 1983 through 1986 were based on two years of reliable roughness data, namely 1979 and 1981. The main reason for using the linear regression

approach was the fact that roughness measurements made during 1980 were not consistent, in most cases, with the roughness readings made in 1979 or 1981.

It is recommended that the roughness number device be calibrated on a routine basis and that the roughness measurements within a given year be monitored at some interval within that year and compared to previous years in order to detect possible calibration problems at an early stage. Appropriate machine adjustments can then be made before it is too late and the entire data set for that particular year is lost.

Recommendations for Further Research

The major reason for developing an optimization model for the PMS in Indiana was to have a systematic tool for the management of resurfacing activities. The optimization routine was formulated as an integer programming model. The LINDO computer program, which uses a branch and bound technique, was used to run the proposed formulations. An analysis was conducted to test the performance variables and to evaluate the coefficients of the objective function as well as the budget constraint coefficients. From this analysis, it is possible to establish resurfacing priorities with some degree of accuracy.

A major lesson learnt in the process of development of the pavement management procedure in Indiana is that a concerned emphasis should be placed on the creation of a centralized data base. At the present time, each Division of the IDOH has its own data subsystem and there is a lack of a common denominator, such as the milepost number, through which each subsystem can be linked together.

In addition, major emphasis should be placed on linking and coordinating the Maintenance Management System with the Pavement Management System. Both systems have many factors in common and the objectives of both systems can be effectively achieved through a combined program.

One of the critical factors in the success of a pavement management system is the careful formulation of the process. Often there is a disagreement among engineers, researchers, and highway managers with respect to the course of action that should be taken to rehabilitate a highway network. The disagreement is in part due to the fact that there are multiple objectives related to highway pavement rehabilitation. For example, the objective of traffic engineers and planners is to provide the best highway service possible, while highway engineers would like to preserve the pavement condition by preventing particular

types of distress. From the management point of view, all objectives are important and the available resources must be used optimally so that the objectives of service, condition, and safety be achieved as closely as possible. In this connection, good judgment based on experience will always be valuable.

There is a misconception that a PMS requires too much data. This is not strictly true. Previous research studies in this area have shown that the additional benefits which can be gained by including all possible performance variables are minimal if the main variables are already included in the original formulation. For example, by including roughness and pavement condition as the two parameters in the computation of the objective function coefficients, the model will generate almost the same sections that it would select if all the performance factors were considered. An analogy to this point of view is the original development of the present serviceability concept. In the original PSI regression model the pavement roughness contributed to over 90 percent of the total variation. At that time, the interstate highway system was being started. At the present time, with over 15 percent of the interstate highway mileage being

classified in "poor" condition a need for pavement condition, evaluation in conjunction with roughness number is evident.

For these reasons, it is also recommended that only those factors absolutely necessary for centrally located computerized data base should be included. Most agencies, which have implemented PMS, have stressed the importance of collecting and storing only relevant data.

There is a need for further research in stochastic characteristics of the performance variables considered in the proposed formulation. The work performed as part of this study showed that the variability in roughness can play an important role depending upon the type of pavement considered and the age of the pavement.

There is also a need for standardized techniques for data collection and measurements so direct comparisons can be made. Major emphasis should be placed by IDOH on the calibration of the PCA roadmeter for future years in order that the data can be effectively used for predicting terminal roughness number. Roughness number, pavement condition, structural evaluation, and skid resistance are the most important parameters regarding how well a highway pavement serves the road user. However, pavement condition and pave-

ment roughness are the two most important factors. The IDOH has initiated a program to collect pavement condition data for only those pavement sections that exceed the trigger numbers associated with roughness. It is recommended that data on both roughness and pavement condition be collected on the entire pavement newtork in two to three year intervals and that both factors be used collectively in deciding what pavement segments should be selected for resurfacing. There may be a pavement section that is rough due to the texture or geometrics of the highway and still be in excellent condition. Roughness number value by itself is misleading; therefore, it should not be used alone for recommending future resurfacing strategies.

Finally, there is an increasing trend by highway agencies in purchasing automated devices that can measure pavement performance parameters and store them directly into disk. The dynaflect, PCA roadmeter, falling weight deflectometer are typical examples. These devices provide the input to a data base with minimum computational time. Along the same lines, the application of microcomputers in almost every field in transportation is increasing rapidly. Management software packages are readily available for most microcomputers in the market. There are various types of computer graphics available. More and more agencies are

using computer graphics with various levels of sophistication to present information to managers and decision makers. There are optimization programs already available in the market for solving small to medium scale linear programming problems on microcomputers. It can be expected that many agencies will make the transition from large computers to microcomputers within the next few years. There will obviously be a need for developing appropriate computer programs for transferring the vast source of information already available for large scale computers into microcomputers. It is recommended that efforts be made by the Indiana Department of Highways to develop programs executable on microcomputers for pavement management evaluation and rehabilitation purposes. The software should be complemented with computer graphics that can be accessed by the user interactively as an option.

In summary, the pavement management program of the IDOH during the coming years should include the development of a centralized data bank, use of microcomputers and associated software for computer graphics, and careful application of an appropriate optimization algorithm including an overlay design routine.

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